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TRANSACTIONS
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ORIGIN AND DEVELOPMENT OF THE AMERICAN GEOPHYSICAL UNION

by
J. A. FLEMING
General Secretary, 1925-1947
Honorary President since 1947

With Foreword
by
Leason H. Adams
President, 1944-1947

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FOREWORD

It is indeed fortunate for geophysics and for the American Geophysical Union that John Adam Fleming has been the one to prepare a concise and factual history of the Union. Of all the men who have been active in this field of science, Dr. Fleming, by his close association with the Union from the earliest days and by his devotion to its interests for a third of a century, is uniquely qualified for this undertaking. A brief statement concerning the author as an investigator, an administrator, and as the guiding spirit of the American Geophysical Union will therefore be an appropriate part of the present record.

John A. Fleming - Honorary President

Before the creation of the American Geophysical Union in 1919 and its implementation in 1920, Dr. Fleming came, in 1904, to the newly established Department of Terrestrial Magnetism of the Carnegie Institution of Washington, following a term of service in the U. S. Coast and Geodetic Survey. At that Department he progressed steadily in duties and responsibilities, becoming successively Assistant Director, Acting Director, and then Director from 1935 until his official retirement in 1947.

In 1925, five years after his election to the Union, Dr. Fleming became its General Secretary, occupying this post until 1947, at which time the office of Honorary President was specially created for him by the Union, and he was given that mark of distinction in partial recognition of his years of unusual service. There are now probably many members of the Union who do not know that for over 20 years he had the energy, and took the time that otherwise might have been used for leisure or recreation, to manage the business affairs of the Union, to edit its Transactions, and to find the means for continuing its publication all through the years.

Dr. Fleming has an impressive record of accomplishments in the field of geophysics. He took an important part in the establishment of magnetic standards; he developed new methods for magnetic measurements on land and sea; and he planned and directed the World Magnetic Survey by the Carnegie Institution of Washington. From 1928 to 1948, he was the Editor and publisher of the Journal of Terrestrial Magnetism and Atmospheric Electricity. He is a Past President of the Philosophical Society of Washington, of the Association of Terrestrial Magnetism and Electricity of the International Union of Geodesy and Geophysics, and of the International Council of Scientific Unions. No mere director of scientific work, his own contributions have been accorded recognition by his election to the National Academy of Sciences, in which he is Chairman of its Section of Geophysics. The American Geophysical Union awarded to him in 1941 its William Bowie Medal in appreciation of his unselfish cooperation in geophysical research, and the Physical Society (London) awarded him in 1945 the Charles Chree Medal. Many other organizations have bestowed honors upon him.

John Adam Fleming, staunch friend of the American Geophysical Union, by right your name should be on every page of the history you have so ably prepared!

Leason H. Adams

Transactions, American Geophysical Union Volume 35, Number 1 February 1954

ORIGIN AND DEVELOPMENT OF THE AMERICAN GEOPHYSICAL UNION, 1919-1952

J. A. Fleming

Abstract--The American Geophysical Union has to do with those theoretical and applied sciences relating to the Earth, its configuration, its structure, and the natural forces acting upon and within it. Since the founding of the Union in 1919, it has gradually developed so that in 1952, with nearly 5000 members, it is perhaps the principal organization in the United States of America acting as a clearing house for new scientific thoughts and ideas relating to Geophysics.

Sponsored by the National Research Council of the National Academy of Sciences, the Executive Committee of the Union is the Committee on Geophysics of the Council and the National Committee for the United States of America of the International Union of Geodesy and Geophysics.

The wide-spread special interests of the eight Sections of the Union are expressed in papers presented at the annual meetings, in the regional meetings (often held in cooperation with other scientific organizations), and in the Union's Transactions, which were formerly published annually and published bimonthly since 1945. Symposia on timely subjects are annual features of the General Assemblies.

The fields of the Sections of the Union are: (a) Geodesy; (b) Seismology; (c) Meteorology; (d) Terrestrial Magnetism and Electricity; (e) Oceanography; (f) Volcanology; (g) Hydrology; and (h) Tectonophysics.

The American Geophysical Union has made every endeavor in the past 33 years to increase coordination and collaboration of interests, both nationally and internationally, and to maintain continuity of the functions of the International Union of Geodesy and Geophysics, thus protecting for future international activities those relations so essential to geophysical investigations, especially during World War II. A prominent Geophysicist of California has said: "The Union, in my opinion, is to be congratulated for having the vision and courage to proceed (during the War) with the annual meetings. The Nation needs more, not less, scientific endeavor."

In these chaotic days following World War II, as never before, responsibility for continued attainment of geophysical knowledge falls with particular emphasis upon the Geophysicists of the Western Hemisphere. Now, as never before, American scientists personally benefit by affiliation with their fellow scientists and co-workers, since the individual worker is under a great handicap. Now, as never before, scientists in general of the Western Hemisphere need to affiliate and play their part not only in the immediate problems of application, in which the Geophysicist is contributing effectively, but in the rehabilitation of international relations and endeavors particularly vital to investigations of the Earth sciences.

This article must be limited to a general account of the origin and development of the Union during the 33 years from 1919 to June, 1952. As a matter of record, detailed particulars of the Union's history are given in the Appendices on subjects as indicated in the Table of Contents.

Early organization--Soon after the establishment of the National Research Council in 1916, Chairman Hale of the Council asked for a memorandum respecting provision to be made for certain geophysical sciences through the concept of the American Geophysical Union even prior to the formation of the International Research Council (designated International Council of Scientific Unions since 1932) and its Union of Geodesy and Geophysics.

In a memorandum prepared by Louis A. Bauer is the statement: "It would appear that great opportunities are before us to make our influence felt in the world of science by which are meant those subjects of research which embrace the Earth or even the universe within their legitimate provinces." In subsequent correspondence with Hale, the term "Geophysics" was defined to include Geodesy, Geological Physics, Meteorology, Terrestrial Magnetism and Electricity, Seismology, and Tides and Oceanography. It was recommended that there be formed a special committee of the Council or a subcommittee of Geophysics dealing especially with world physical sciences. Stimulation was given to the project as early as 1916 at a joint meeting of the American Physical Society and the Section of Physics for the American Association for the Advancement of Science in a paper by Bauer entitled Our Part in the Advancement of World Physical Sciences. Following the establishment in 1918 of the International Research Council, when World War I was drawing to a close, there was tentatively established by the National Research Council an American Section of the proposed International Geophysical Union, one of the bodies contemplated by the International Research Council. In all the early documents, the purpose seems to have been to provide a meeting ground for men having points of contact and common interest in geophysical research. This already had been accomplished in Great Britain by July, 1917, when a special Committee on Geophysics was appointed by the British Association for the Advancement of Science. The British Committee on Geophysics held its first meeting in London during November, 1917; that Committee has had geophysical meetings quite frequently ever since.

In December, 1918, Chairman Hale of the National Research Council appointed a small committee to consider the question of the organization of an American Section of the proposed International Geophysical Union and named R. S. Woodward as Chairman. Woodward's report of March 4, 1919, addressed to the Chairman of the National Research Council, is quoted as a major stone in the eventual foundation of the American Geophysical Union:

> Your Committee appointed to consider the question of a logical and practicable organization of the proposed American Section of the International Geophysical Union respectfully submits the following report:
>
> The Earth is at once the subject and the object of many sciences. Of these the most important are Astronomy, Geodesy, Geology, Meteorology, Seismology, Terrestrial Magnetism, Terrestrial Electricity, Tides, and Volcanology.
>
> While each of these sciences is more or less distinct in itself, they are closely related to one another, and progress in any one of them may be expected to depend to a great extent on the general progress attained in the others. Each of these sciences has its devotees and its experts, and the number of these in the aggregate is now very large. Hence in any scheme of effective organization it is essential to secure groupings of these various subdivisions of Geophysics in order that the number of groups may not be too unwieldy in the transaction of business essential to such organizations. But it should be distinctly understood that in recommending a limited number of groups for purposes of administration it is not desired to discourage relations of closest reciprocity between the devotees to the various sciences included in the groups. On the contrary, it is the opinion of your Committee that progress in the future is most likely to result from active cultivation of the borderlands that now serve to distinguish, but only indefinitely, the several fields of Geophysics.
>
> It should be understood also that the groupings recommended are to be regarded as provisional and subject to such changes as future experience may suggest. It is recognized also that the groupings here recommended may not be the most appropriate for all countries or possibly for an international organization, since much regard should be given in all such matters to historical precedents and to the circumstances presented at any epoch by individual investigators, and especially by governmental organizations, of any country.
>
> With these reservations the Committee recommends that the following groups of subjects should be recognized in the organization of the American Section of the International Geophysical Union:
>
> Group 1: Geodesy--This group may be assumed to deal with questions concerning the size, the shape, and the mechanical properties of the Earth.
>
> Group 2: Seismology and Volcanology.
>
> Group 3: Meteorology and Mareology, including especially all questions presented by the mechanical properties of the atmosphere and the oceans.
>
> Group 4: Terrestrial Magnetism and Terrestrial Electricity--This group is intended to deal with the magnetic and electric properties of the Earth, including its atmosphere.
>
> The Committee recommends that initially the designation of members to constitute the proposed Geophysical Section be made by the National Academy of Sciences. It is further recommended that in making such designations regard be had to the desirability of securing representatives from the following Government Bureaus: Bureau of Fisheries; Bureau of Mines; Bureau of Standards; Coast and Geodetic Survey; Hydrographic Office, U. S. Navy; Geological Survey; Weather Bureau.
>
> Similarly, the Committee suggests that representatives also may be fitly chosen from the following national societies: American Astronomical Society; American Mathematical Society; American Physical Society; Geological Society of America; Seismological Society of America.
>
> The Committee further recommends that, in order to promote research and discovery in geophysical science in general, steps be taken by the American Section of the International Geophysical Union toward the formation of a new society to be called the American Geophysical Society.

The Executive Committee of the Division of Physical Sciences of the Council approved the organization and initial membership of the American Section on Geophysics on March 10, 1919 (see Appendix A). This action was soon thereafter approved by the National Academy of Sciences. On

April 15, 1919, the Executive Board of the Council named a Provisional Executive Committee of the American Section of the International Geophysical Union. The first meeting of this Committee was held in Washington, D. C., May 20, 1919. Members present were William Bowie, Gross, Leuschner, Marvin, Peters (representing Bauer), Reid, Woodward, and, by invitation, Wood.

A. O. Leuschner quoted the following recommendations from the minutes of the joint meeting of the Executive Board and the Council of the National Academy of Sciences: The formation of an American Section of the proposed International Geophysical Union was tentatively approved with the provision that the subjects to be included and their grouping be determined by the Section after its permanent organization, reference to the Section of the question of the formation of an American Geophysical Society, and nomination on behalf of the Executive Committee of the Division of Physical Sciences for membership in the Section. These were adopted.

William Bowie, Moulton, and Marvin were appointed a Committee on Variation of Latitude of the American Section of the International Geophysical Union, to confer with a similar Committee of the American Section of the International Astronomical Union and to make joint recommendations with that Committee as regard future organization of researchers on the variation of latitude.

Bauer, William Bowie, Cross, Reid, Marvin, and Leuschner, with Woodward as Chairman, were appointed to prepare recommendations regarding international cooperation in geophysical subjects for consideration by the American Section of the International Geophysical Union, with the understanding that this Committee had power to increase its membership.

Following the appointment of William Bowie as Acting Chairman of the American Section of the International Geophysical Union, an organization meeting of the Section was designated to be held in Washington in conjunction with the meeting during June, 1919, of the American Section of the International Astronomical Union, and H. O. Wood was made a member of the American Section and designated as its Secretary.

Committees of one were appointed to prepare brief statements in regard to the past history, present status, and scientific purposes of: (1) International Geodetic Association; (2) International Seismological Association; (3a) International Meteorological Committee; (3b) International Committee for the Study of Free Atmosphere; and (4) International Commission of Terrestrial Magnetism.

Those appointed were Bowie for (1); Reid for (2); Marvin for (3a) and (3b); and Peters for (4). Instructions were also given that the Chairman of the small Committee prepare a brief general statement in regard to the past history, present status, and scientific purposes of Geophysics in general.

For the information of this Committee, the British proposals for the Convention of an International Union of Geophysics under the International Research Council were read and Leuschner was requested to prepare a clarifying statement in regard to foreign proposals.

This led to a discussion of the appropriate place of Volcanology and other subjects in the organic scheme of the International Union of Geodesy and Geophysics. To illustrate the difference of opinion as regards classification, a letter from C. E. Mendenhall of the Office of the Scientific Attaché Research Information Service at the American Embassy in London, conveyed the attitude of the Royal Society of Great Britain as to its attitude on the subject of Vulcanology:

> The Royal Society feels that all branches of volcanology, except those using seismological methods and observations, are essentially geological in character and are largely in the hands of geologists at present. In this opinion I imagine that Dr. Cross would agree with them, but their way of handling the situation is exactly opposite to that of Dr. Cross. They feel that the geophysical organization is already so complex and involves so many connections with other subjects that it would be better in this case not to attempt to embody the whole subject of vulcanology under geophysics and to establish the liaison with geology, which would be necessary in that case, but rather to establish the subject definitely under geology and then let the geologists establish the necessary liaison with the Seismological Section of the Geophysical Union. This, of course, represents only the recommendation of the Royal Society, and it does not follow that it will necessarily be adopted at the Brussels Meeting.

As a result of the discussion, various members of the Committee were requested to prepare statements regarding the subdivisions of geophysical science in their international aspects for consideration at its second meeting, which was held March 11, 1920. At the second meeting of this Committee reports were heard from the Committees on Statutes and By-Laws and on the First Annual Meeting to be held on April 23, 1920. A preliminary meeting of the tentative American Section of the proposed American Geophysical Union was held in Washington on June 24-25, 1919. At that time, the Council of the Academy was not prepared to recognize the need of a special body for Geophysics alone, and considered that the desired object could be attained by merging Geophysics with Geography. But, soon after this action, a more distinctive recognition was granted Geophysics in that it was mentioned specifically in the title of one of the more important divisions of the organization of the National Research Council, namely, the Division of Physics, Mathematics, Astronomy, and Geophysics.

At the close of World War I and the reorganization of the National Research Council on a peace basis, the question arose as to how best to secure representative membership for the various Divisions of the Council, Physical Sciences, Chemistry, Geology, and others. For those sciences which had national societies, the solution was relatively easy as representatives could be recruited through the Division of Physical Sciences from recommendations made to the National Research Council by the American Physical Society, the American Astronomical Society, the American Mathematical Society, and so on. Representatives for the geophysical sciences, however, could not be so easily chosen because the only society then interested in Geophysics was the Seismological Society of America, and there were no distinct national societies for Geodesy, Terrestrial Magnetism and Atmospheric Electricity, Volcanology, Oceanography, and Geophysical Chemistry. It was not until later that the American Meteorological Society was organized.

The second meeting of the Provisional Executive Committee in June, 1919, was followed by a preliminary meeting in Washington, D. C., of the tentatively organized American Section of the proposed International Geophysical Union on June 24-25, 1919.

William Bowie acted as Chairman at this meeting and it was agreed that permanent organization be deferred until after the first international meeting was held in Brussels. The proposal that the Geophysical Committee be a part of the Division of Physical Sciences and concern itself with national, as well as international, problems in Geophysics was agreed to. Delegates were appointed to the Brussels Meeting and resolutions were adopted respecting various matters of interest to the organization and Section of the proposed International Union. The delegates (William Bowie, Bauer, and Marvin) were also named a committee to draft a plan for the permanent organization of the American Section after the Brussels Meeting during July 18-28, 1919.

On November 13, 1919, the Secretary of the tentative American Section transmitted to the members, Proposals for the Permanent Organization and Statutes of the American Geophysical Union. These were prepared by a subcommittee, after giving careful consideration to: (1) the structure and Statutes of the International Research Council, and the International Union of Geodsey and Geophysics, definitely formed at Brussels in July, 1919; (2) the present relations of the existing American Section of the proposed International Geophysical Union to the National Research Council, and the relations considered desirable in future; and (3) views expressed by present members especially at an informal conference of the Committee of the Brussels geophysical delegates with members of the American Section who reside in or near Washington, D. C. This conference was held on October 31, 1919, at the National Research Council; there the subcommittee had the benefit of extended discussion with Chairman Mendenhall of the Council's Division of Physical Sciences, and with Washington, both of whom were present at Brussels. Secretary Wood further stated in his transmitting letter:

> The present status of the American Section is that of a Committee of the Division of Physical Sciences of the National Research Council. This status it will retain until it is discharged as such, or until it is superseded by the adoption, as of some definite date, of proposals for permanent organization which change its status. In this connection it has seemed best to the Committee on Organization to recommend that the proposed American Geophysical Union be made a Committee of the Council as a whole, and that the Union be so constituted as to unite and coordinate in our country the interests of physics, chemistry, and geology in geophysical questions.
>
> The name American Geophysical Union was settled upon as the result of careful consideration and evolution of various preliminary drafts. Thus, instead of Union it was originally proposed to use the term Committee, and later Commission; however, as progress was made in drawing up the proposals, the need of a more appropriate term became evident. Thus, the American Geophysical Union, as proposed, is a union of two distinct committees, namely, the American National Committee of the International Geodetic and Geophysical Union, and the Committee on Geophysics of the National Research Council. In the absence of

an American Geophysical Society in the United States, the proposed Union would seek to bring together and coordinate all societies, bodies, and institutions in the United States interested in geophysics.

The proposals were unanimously approved by the Executive Board of the National Research Council on December 20, 1919. On February 20, 1920, the American Geophysical Union was made a Committee of the Executive Board of the Council, and its first meeting, as a Union, was held on April 23, 1920.

The records for the earlier years are fragmentary and the materials for the section on Early Organization (p. 5 and following) have been, of necessity, largely taken from Louis A. Bauer's The Organization and Aims of the American Geophysical Union, presented at the Annual Meeting, April, 1923 [Bull. Nat. Res. Council, no. 41, pp. 7-18, 1924; see also H. O. Wood, Science, v. 50, pp. 233-238 and 255-259, 1919].

History and functions--Thus the American Geophysical Union (AGU) was created in 1919 as an Executive Committee by the National Research Council of the National Academy of Sciences (NRC NAS) to function as the American National Committee of the International Union of Geodesy and Geophysics (IUGG) and the Committee on Geophysics of the NRC. Its defined duties are "to promote the study of problems concerned with the figure and physics of the Earth, to initiate and coordinate researches which depend upon international and national cooperation, and to provide for their scientific discussion and publication." Presently these duties are organized under eight Sections of the Union, namely: Geodesy, Seismology, Meteorology, Terrestrial Magnetism and Electricity, Oceanography, Volcanology, Hydrology, and Tectonophysics. These fields are briefly described in Appendix D. The Statutes and By-Laws, as amended to July 31, 1950 (no subsequent changes), are shown in Appendix B.

The original limit in number was 65. This limit held until April, 1922, when it was set at 75. Late in 1928 it was revised to 100, and in April, 1930, the limit was removed by action of NRC. From 1919 to 1931 funds required for the expenses of the Union were provided by NRC. Because of the rapid growth and extension of interests, it was arranged that from 1932 annual contributions ($2 through 1936, $3 during 1937 to 1945, $5 during 1946 to 1949, and $7 since 1950) be made by each person associated with AGU. The annual aid from NRC was reduced to $400. Nearly 5000 qualified persons are now collaborating as annual contributors; about one-half of these were enrolled during 1944 to 1950 [see Appendix I]. Printed alphabetical lists of members and officers are published about every two years.

A list of the officers of the Union and its Sections from the founding up to 1952 is presented in Appendix C.

An important milestone in the history was passed in 1939 when Richard M. Field, then President of AGU, brought to successful culmination the establishment of the William Bowie Medal, the award of which has been described by impartial observers as "about the highest honor a man in (this) field can receive." More details regarding the establishment and award of this Medal are given in Appendix E.

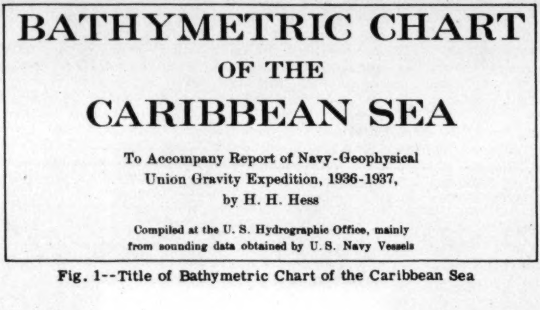
National responsibilities--The AGU serves national interests in its specified duties in coordinated fact finding and applications of the dynamics of Earth sciences in part through (1) annual meetings (33 were held in Washington through 1952) for presentation and discussion of scientific papers and progress reports in the eight branches of Geophysics and their interrelations and interpretations, and (2) regional meetings (27 since 1934; see subsequent section entitled Regional meetings) for similar agenda. These annual and regional meetings, appraised by competent authorities to be most stimulating and profitable, afford unique opportunities for contact and discussion among leading investigators and for the promotion and development of knowledge and applications in the related fields. In the earlier years communications were received annually not only from the United States but also from Canada, Mexico, Central America, and some of the South American countries. The rapidly increasing knowledge in all fields of Geophysics, for example, from the determination of dynamics of soil erosion, cosmic relations of radio wave propagation, to forecasting water resources from snow surveys within the past few years, has enlarged the responsibilities of the Union in national progress.

International responsibilities--The AGU serves international interests in studies of natural Earth forces that condition human endeavor and progress in making use of the Earth's resources, of land, of minerals, and of water, and must have world-wide coordination of effort, that is, cooperation which is unrestricted by national boundaries. The Union has taken prominent part, through designation of delegates by NRC and NAS upon the Union's recommendation to the triennial assemblies of the IUGG. (So far nine assemblies, usually triennial, have been held, namely: Rome in 1922, Madrid in 1923, Prague in 1927, Stockholm in 1930, Lisbon in 1933, Edinburgh in 1936, Washington in 1939, Oslo in 1948, and Brussels in 1951.) These meetings have coordinated and stimulated international plans and efforts. During the War the AGU was an important factor in maintaining continuity of international activities, which otherwise would have lapsed. It thus insured normal and effective postwar rehabilitation of the IUGG. In particular, the AGU has taken part in enlarging the interest and participation of the other countries of the Western Hemisphere in Geophysics.

Publications--The AGU serves science by advancing knowledge and facilitating applications of dynamics to Earth forces and materials. This is done through the publication of scientific papers, discussions, and reports at the annual and regional meetings in the Union's Transactions (for list, corrected through January, 1954, see Appendix J). Up to 1944 these included 22 annual volumes with 31 separate parts. Since August, 1945, the Transactions have been published bimonthly. Through the method of offset printing directly from prepared copy, the all-inclusive cost of publication has been remarkably low. Some 17,767 pages have been published since 1920 (equivalent to about 25,000 pages in the usual conventional printed format) in editions of 2000 and over at a rate per page much less than the cost for ordinary letter-press printing. Volumes 1 to 25 (1920-1944) total 11,053 pages, and Volumes 26 to 33 (through Part 3) of the bimonthly series of the Transactions total 6714 pages. The number of each issue printed by the offset method is now 5600. The Transactions are distributed to those enrolled in the Union, to reviewing journals, and by subscription and gift to nearly 1000 geophysicists and interested organizations and libraries abroad. Other publications (see Appendices J and K) include five volumes and 49 exhibit maps concerned with the Washington Assembly of IUGG in 1939, a series of annual bibliographies of American hydrologic literature from 1935-1940, and an index to the Transactions from 1920-1944. Until 1944 the editing and preparation of master copy for publication was done gratuitously in the spare time of officers of the Union, particularly its General Secretary. Since August, 1945, the Transactions have been published bimonthly (each issue containing 150 pages or more), and the editing has been done by the members of the Editorial and Publication Committee.

Opportunity--The opportunity for enlarged service to our national and international contributions in Earth sciences is almost boundless. The following are typical examples of the Union's usefulness in obtaining international and national cooperation.

(1) The AGU sponsored and organized two naval expeditions to the Caribbean. These would hardly have been attempted by private organizations. They represented a cost equivalent to hundreds of thousands of dollars in the use of surface and subsurface vessels and scientific personnel and equipment made available, largely upon the Union's solicitation, by governmental and research organizations (United States Navy, Department of State, American Telephone and Telegraph Co., Princeton University, Carnegie Institution of Washington, Woods Hole Oceanographic Institution, the Dutch Government, and others). The results of this are shown by the Bathymetric Chart of the Caribbean Sea of the Hydrographic Office [H. O. Miscell. 9062, 26 1/2 by 50 inches; a limited supply of these maps is available through the American Geophysical Union and copies will be inserted in reprints of this paper], the title of which is reproduced here as Figure 1. The opportunity for enlarged service of the Union to national and international contributions to the scientific aspects of the Earth sciences seems almost boundless. This expedition is an outstanding example.



BATHYMETRIC CHART
OF THE
CARIBBEAN SEA

To Accompany Report of Navy-Geophysical
Union Gravity Expedition, 1936-1937,
by H. H. Hess

Compiled at the U. S. Hydrographic Office, mainly
from sounding data obtained by U. S. Navy Vessels

Fig. 1--Title of Bathymetric Chart of the Caribbean Sea

(2) Just before the outbreak of World War II the Union, in collaboration with the National Geographic Society and the University of Virginia, had obtained authority for the use, during one year, of a United States Coast Guard 300-foot cutter with complete complement of men, and had secured scientific personnel and equipment from various research organizations for extensive geophysical and biological surveys in the area of the South Pacific Islands, all without expense to AGU, and with the gratuitous services of scientific investigators, an unique example of use of facilities requiring coordination and cooperation. The large practical and scientific additions to knowledge that would have resulted, had not the War interfered just when arrangements had been made and equipment in large measure assembled on the West Coast, can hardly be estimated.

(3) The AGU has not only stimulated organization of major expeditions, as in (1) and (2), for the securing of needed data, but was also active in fostering coordinated analyses, and the diffusion of new information thus obtained. This was partly brought about through the Union's cooperation in sponsorship and presentation of joint symposia; examples are (a) The Geophysical Exploration of the Ocean Bottom, with the American Philosophical Society, and (b) The Surface and Subsurface Exploration of Continental Borders, with Sections D (Astronomy) and E (Geology and Geography) of the American Association for the Advancement of Science.

It is this type of catalytic functioning in many fields which the AGU can bring about with comparatively little actual expenditure of its own funds and without burden upon scientific endowments.

Effect of the War--The War greatly increased the demands upon the resources of the Union by reason of (1) increased costs, (2) increased number of associates in the armed forces and the consequent increased burden upon those available to continue essential and expanding operations, not only because of applications to the war effort but also the rapidly enlarging potential applications in postwar progress, and (3) increased need of maintenance to safeguard continuation of international progress and cooperative effort.

Postwar and present needs--The continued and future success of the AGU depends upon (1) publication of Transactions, (2) moderate financial aid besides that contributed by its present 5000 associates to overcome the handicap caused by the abnormal conditions induced by the War, and (3) a paid full-time Executive Secretary and staff. To meet these pressing needs the AGU planned, in 1943, to establish a financial basis consonant with the opportunities to advance geophysical knowledge and applications in both international and national undertakings. To this end additional special voluntary contributions from associates were solicited in a total of $10,000 toward the estimated goal of $30,000 required for the three years from July 1, 1944, to June 30, 1947; the additional $20,000 required to realize this total was generously granted by the Rockefeller Foundation in 1944. By 1947, and with the return of normal conditions, the number of persons associated with AGU had so increased that the annual contributions became sufficient to meet fully the expenses of maintenance and future development.

In the mid 1940's, the contribution of voluntary services had become such a heavy burden under existing conditions with the increasing responsibilities of the Union that it could not equal the need. Continued and enlarged functioning, in keeping with the growing opportunity, was provided by the appointment of a full-time paid Executive Secretary and staff of three beginning in September, 1944.

Thus, for the purpose of serving more effectively the sciences dealing with the Earth itself and of ultimately applying such knowledge more efficiently to the advancement of human interests, the AGU has now (1952) placed its operations on an independent footing, and now that the Union is functioning as it should, it is in a position to meet its many opportunities and responsibilities for national and international progress.

Annual General Assemblies--As stated above, the objects of the Union are to promote the study of problems concerned with the figure and physics of the Earth, to initiate and coordinate researches which depend upon international and national cooperation, and to provide for their scientific discussion and publication. To this end, the Union is divided into the eight Sections cited earlier, following the general plan of organization of the International Union of Geodesy and Geophysics. A Section of Geophysical Chemistry was discontinued May 31, 1924, as the International Union had failed to provide such a Section. The Section of Hydrology was established November 15, 1930; matters pertaining to scientific hydrology referred to the AGU were previously looked after by Special Committees on Hydrology. The Section of Tectonophysics (a Section not included in the IUGG) was established April 9, 1940, for the purpose of promoting and encouraging research of fundamental importance to our knowledge of Earth structure not covered in any one of the other Sections of the Union.

General Assemblies of the Union and meetings of its Sections for presentation and discussion of papers and symposia are held in Washington, D. C., each year. A brief account of these is presented in Appendix F. The first Annual Meeting or Assembly of the Union was that of 1920.

One of the unusual features of the Union is, of course, the possibility it offers for personal contacts, nationally and internationally, among geophysicists everywhere. In the early years, when membership was small, dinners were frequently arranged at the time of annual meetings; in later years, beginning in the 1930's, smokers, with light refreshments, have been arranged and have proved very valuable in providing social contact, and opportunity for meeting colleagues on a purely informal basis. Appendix G provides an example of the earlier phase of this Union activity.

Regional meetings--Following the formation of the Section of Hydrology, regional meetings were held usually jointly with other organizations having coordinated interests. For the purpose of such meetings, the Executive Committee of the Section of Hydrology originally designated selected regional areas, namely: North Continental Divide -- Montana, Idaho, eastern Washington, eastern Oregon, and Alberta (affiliated); South Continental Divide -- Colorado, Wyoming, Utah, and New Mexico; North Pacific Coast -- western Washington, western Oregon, Alaska, and British Columbia (affiliated); South Pacific Coast -- California, Nevada, Arizona, and Hawaii. Besides the regional meetings sponsored by the Section of Hydrology, the Union has also encouraged joint meetings with organizations and societies interested in the discussion of various aspects of the geophysical sciences.

Thus far, regional meetings have been held as follows (references to publication of proceedings given refer to the Transactions of the Union, part and year):

(1) South Pacific Coast Area at Berkeley, California, jointly with Western Interstate Snow Survey Conference, June 20-21, 1934 [pt. 2, 1934, pp. 522-633].

(2) South Pacific Coast Area at Pasadena, California, jointly with Western Interstate Snow Survey Conference, January 31-February 1, 1936 [pt. 2, 1936, pp. 455-562].

(3) South Continental Divide Area at Denver, Colorado, jointly with South Continental Divide Snow Survey Conference and with the Society of American Foresters, June 21-26, 1937 [pt. 2, 1937, pp. 509-663, with addendum in pt. 2, 1938, pp. 668-669, and Journal of Forestry, v. 35, pp. 991-1055, 1937].

(4) North Continental Divide Area at Spokane, Washington, December 28-29, 1937 [pt. 2, 1938, pp. 590-594].

(5) South Pacific Coast Area at Davis, California, jointly with Western Interstate Snow Survey Conference, January 7-8, 1938 [pt. 2, 1938, pp. 595-667 and 672-743].

(6) South Pacific Coast Area at Los Angeles, California, jointly with the Western Interstate Snow Survey Conference, December 16-17, 1938 [pt. 1, 1939, pp. 3-96].

(7) Symposium on The Surface and Subsurface Exploration of Continental Borders, at Richmond, Virginia, jointly with Sections D and E of the American Association for the Advancement of Science, December 27, 1938 [pt. 3, 1940, pp. 781-826].

(8) North Continental Divide Area at Spokane, Washington, jointly with the Western Interstate Snow Survey Conference, December 28, 1938 [pt. 1, 1939, pp. 97-138].

(9) South Pacific Coast Area at Stanford University, California, jointly with the Western Interstate Snow Survey Conference, January 12-13, 1940 [pt. 1, 1940, pp. 3-143].

(10) Symposium on Applications of Mathematics in the Earth Sciences, and Hydrologic Problems in the Ohio and Michigan Basins, at Columbus, Ohio, jointly with Sections A and E of the American Association for the Advancement of Science, the American Mathematical Society, the Mathematical Association of America, and the Geological Society of America, December 29, 1939 [pt. 4, 1940, pp. 1065-1146].

(11) North Pacific Coast and North Continental Divide Areas at Seattle, Washington, jointly with the Western Interstate Snow Survey Conference and Section E of the American Association for the Advancement of Science, June 19-22, 1940 [pt. 3, 1940, pp. 831-1061].

(12) South Pacific Coast Area at Sacramento, California, jointly with the Western Interstate Snow Survey Conference, January 16-18, 1941 [pt. 1, 1941, pp. 5-216].

(13) Symposium on Relation of Geology to the Ground-Water Problems of the Southwest, at Dallas, Texas, jointly with the American Association for the Advancement of Science, December 30, 1941 [pt. 1, 1942, pp. 3-56].

(14) South Pacific Coast Area at Pasadena, California, jointly with the Western Interstate Snow Survey Conference, January 16-17, 1942 [pt. 1, 1942, pp. 57-171].

(15) North Pacific Coast Area at Corvallis, Oregon, jointly with the Western Snow Conference, June 16, 1943 [pt. 3, 1943, pp. 1-99, and Addendum on pp. A1-A3].

(16) South Pacific Coast Area at Berkeley, California, jointly with the Western Snow Conference and Pacific Coast Section of the American Society of Agricultural Engineers, February 17-18, 1944 [pt. 1, 1944, pp. 3-185].

(17) South Pacific Area at Los Angeles, California, February 27, 1945. (The Transactions were published bimonthly beginning in August, 1945, and from that date onward papers have no longer been printed as a unit, related to a particular meeting, but individually.)

(18) South Pacific Area at Sacramento, California, jointly with the Pacific Coast Section of the American Society of Agricultural Engineers and the Western Snow Conference, February 26-28, 1946.

(19) South Pacific Area at Pasadena, California, February 15, 1947.

(20) North Pacific Area at Portland, Oregon, jointly with the Western Snow Conference and the Columbia Basin Water Forecast Committee, April 21-23, 1947.

(21) New England Meeting at Middletown, Connecticut, at Woods Hole, Massachusetts, and at Cambridge, Massachusetts, September 17-19, 1947 (meeting at Cambridge jointly with the American Meteorological Society).

(22) South Pacific Coast Area, Sections of Hydrology, Oceanography, and Meteorology, at Berkeley, California, February 13-14, 1948.

(23) South Pacific Coast Area, Sections of Hydrology and Meteorology, at Los Angeles, California, February 4-5, 1949.

(24) South Continental Divide Area at Denver, Colorado, jointly with the Western Snow Conference, April 26-28, 1949.

(25) South Pacific Coast Area, Sections of Meteorology and Hydrology, at Davis, California, February 3-4, 1950.

(26) South Pacific Coast Area, Sections of Meteorology and Hydrology, at Fresno, California, February 9-10, 1951.

(27) Pacific Southwest Region, Sections of Meteorology and Hydrology, at Pasadena, California, February 8-9, 1952.

Following World War II, there was considerable sentiment for the increase of regional activity, extending it, possibly, to all Sections. Merrill Bernard was appointed chairman of a special committee to study the problem, and after an extensive survey a report was adopted [see Trans., v. 30, pp. 936-939, December, 1949] establishing a very flexible plan of regionalization. The Pacific Southwest Region is the only one formally organized under the plan [for By-Laws, see Trans., v. 33, pp. 629-630, August, 1952], but sentiment for regional activity is growing in other regions, and others will no doubt be organized in due course.

Student subscriptions--In 1948, a special committee (Chairman W. C. Jacobs and Florence Robertson) was established to study the problem of a possible student membership. The Committee did not find among universities and other institutions of higher learning any significant student population that could be conveniently and significantly brought into a student group or chapter form of membership. Though the report [Trans., v. 31, pp. 648-649, August, 1950] was generally favorable to the establishment of such a membership, questions were raised if the likely number of such memberships would justify the necessary changes in the Statutes and By-Laws. It was subsequently decided [Trans., v. 32, p. 146, February, 1951] that, as a trial, a student subscription be established at a rate to be set by the General Secretary that would defray costs. (The rate of $4 was subsequently established.) Since that action, the number of student subscriptions has been about 20 per year; this small number justifies the judgment of the Executive Committee. It is a natural consequence of the fact that files of the Transactions are found in practically every library of universities offering courses in any aspect of the broad field of Geophysics.

Miscellaneous--Since 1925, the Union has had, without charge, office quarters and storage space with the Carnegie Institution of Washington first at its Department of Terrestrial Magnetism (5241 Broad Branch Road, Northwest, Washington 15, D. C.) until 1947, and then at the Administration Building of the Institution (1530 P Street, Northwest, Washington 5, D. C.). This has taken an important part in the economical operation of the Union, one certainly equivalent to an annual gift of not less than $2000. Grateful acknowledgments of this have been made by resolutions unanimously adopted at each Annual Meeting.

Review of Appendix H on finances of the Union from 1932 to June, 1952, shows how generously the Rockefeller Foundation of New York and the Geological Society of America have aided the progress of the Union by substantial grants-in-aid.

The relation of the Union to, and the sponsorship by, the National Research Council of the National Academy of Sciences and the continued annual grants of the Council have also greatly aided the Union in its attainment of the recognition of Geophysics as a profession. That progress has been more definitely indicated by the establishment, within the Academy, of a formal Section of Geophysics on July 1, 1951, presently (June, 1952) numbering 20 members, following the elections to membership in the Academy of eminent geophysicists of the United States as sponsored by the Temporary Nominating Committee on Geophysics of the Academy during the preceding nine years.

APPENDIX A--MEMBERSHIP OF PROVISIONAL COMMITTEE OF AMERICAN SECTION, PROPOSED INTERNATIONAL GEOPHYSICAL UNION, APRIL, 1919, TO APRIL 23, 1920, AND OF MEMBERSHIP OF AMERICAN GEOPHYSICAL UNION FOR FIRST TEN ANNUAL MEETINGS, 1920-1929

Membership[a] of "American Section of the proposed International Geophysical Union" as of July 1, 1919, and members elected before first Annual Meeting of AGU, April 23, 1920

C. G. Abbot
S. J. Barnett (5)[b]
Joseph Barrel (1) [1919][c]
L. A. Bauer (5) [1932]
H. B. Bigelow (4)
W. R. Blair (3) [1949]
E. H. Bowie (3) [1943]
William Bowie (1) [1940]
J. C. Branner (2) [1922]
L. J. Briggs
E. W. Brown (1) [1938]
Whitman Cross (2) [1949]
R. A. Daly (2)
W. M. Davis [1934]
A. L. Day (2)
R. F. Faris (5) [1932]
H. C. Graves (4) [1919]
G. E. Hale [1938]
J. F. Hayford (1) [1925]
D. L. Hazard [1951]
A. J. Henry [1931]
L. M. Hoskins [1937]
W. J. Humphreys (3) [1949]
T. A. Jaggar [1953]
A. O. Leuschner (1) [1953]
G. W. Littlehales (4) [1943]
C. F. Marvin (3) [1943]
Max Mason (dropped 1921)
S. J. Mauchly [1928]
A. G. Mayor (4) [1922]
A. G. McAdie (3) [1943]
G. F. McEwen (4)
A. A. Michelson (4) [1931]
R. A. Millikan (3) [1953]
F. R. Moulton (4) [1952]
G. P. Paine [1929]
F. A. Perret [1943]
W. J. Peters [1942]
H. F. Reid (2) [1944]
F. Schlesinger (1) [1943]
R. B. Sosman (2)
W. F. G. Swann (5) (resigned 1953)
C. E. Van Orstrand (resigned 1952)
R. DeC. Ward [1931]
J. T. Watkins (4) (resigned 1926)
H. O. Wood (2)
R. S. Woodward (1) [1924]
J. B. Woodworth [1925]

Elected after First Annual Meeting, April 23, 1920, through Tenth Annual Meeting, April 25-26, 1929[d]

L. H. Adams
O. S. Adams
E. T. Allen
John A. Anderson (resigned 1953)
J. P. Ault [1929]
L. W. Austin [1932]
H. G. Avers [1947]
W. D. Bancroft (resigned 1933)
D. C. Barton [1939]
N. L. Bowen
Austin H. Clark
F. W. Clarke [1931]
H. H. Clayton [1946]
J. H. Dellinger
C. N. Fenner [1949]
Charles J. Fish
J. A. Fleming
Oliver H. Gish
W. R. Gregg [1938]
J. W. Greig
Harvey C. Hayes (dropped 1934)
N. H. Heck [1953]
C. A. Heiland
C. V. Hodgson [1929]
E. O. Hulburt
C. O'D. Iselin
Lewis V. Judson
H. H. Kimball [1944]
W. D. Lambert
Esper S. Larsen, Jr.
A. C. Lawson [1952]
J. B. Macelwane
H. A. Marmer [1953]
H. E. McComb [1952]
W. C. Mendenhall (resigned 1934)
H. E. Merwin
H. F. Moore [1939]
George W. Morey
R. C. Murphy (resigned 1950)
Frank Neumann
William E. Parker [1942]
G. T. Rude (resigned 1946)
Waldo L. Schmitt
E. S. Shepherd [1949]
Edward H. Smith
George Steiger [1944]
C. H. Swick
F. A. Tondorf [1929]
S. D. Townley [1946]
M. A. Tuve
T. Wayland Vaughan [1952]
G. R. Wait [1953]
H. S. Washington [1934]
Roger C. Wells [1944]
Frank Wenner
Bailey Willis [1949]
Fred E. Wright [1953]
E. G. Zies

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[a] Ex-officio members not listed were the Chairmen of the five Divisions of the National Research Council: Chemistry (W. D. Bancroft in 1919, who was elected to AGU in May, 1920, after expiration of appointment as Chairman in 1919-20); Biology and Agriculture (C. E. McClung in 1919-20 [1946]); Geography and Geology (E. B. Mathews in 1919-20 [1944]); Physics (C. E. Mendenhall in 1919-20 [1935]); Foreign Relations (G. E. Hale in 1919 [1938], who was elected to AGU in March, 1920, after expiration of appointment as Chairman).

[b] The figure in parentheses following name indicates geophysical field in tentative American Section of the proposed International Geophysical Union, namely: (1) Geodesy; (2) Seismology; (3) Meteorology; (4) Physical Oceanography; (5) Terrestrial Magnetism.

[c] Indication in brackets following name is the year of death of the individual.

[d] Total net membership excluding five ex-officio members, namely, Chairmen of Divisions of National Research Council, as of April 26, 1929, was 95.

APPENDIX B

NATIONAL RESEARCH COUNCIL

AMERICAN GEOPHYSICAL UNION

STATUTES AND BY-LAWS

(Originally adopted at organization in 1919 and as amended to July 31, 1950)

PREAMBLE

The American Geophysical Union is hereby established by the National Research Council. It supersedes the "American Section of the proposed International Geophysical Union." The American Geophysical Union is the American National Committee of the International Union of Geodesy and Geophysics and the Executive Committee of the American Geophysical Union is the Committee on Geophysics of the National Research Council.

STATUTES

Article 1: Objects--(a) To assist in carrying out the objects of the International Union of Geodesy and Geophysics, which are: To promote the study of problems concerned with the figure and physics of the Earth; to initiate and coordinate researches which depend upon international cooperation, and to provide for their scientific discussion and publication; and to facilitate special researches.

(b) To promote, coordinate, and facilitate the study of the various branches and interrelationships of geodesy and geophysics in the United States of America, its outlying territories, and the ocean; to provide for scientific discussion, publication, and dissemination of information relative to these fields through the Transactions of the American Geophysical Union and other means.

Article 2: Bequests, Grants, Contributions, and Funds--The Union, upon approval of the National Research Council, may receive bequests, grants, contributions, and funds and may make disbursements therefrom, upon approval of the National Research Council.

Article 3: Membership--The membership of the American Geophysical Union shall be as follows:

(a) Members--(1) Those who composed the membership of the "American Section of the proposed International Geophysical Union" on July 1, 1919.

(2) Citizens of the United States of America engaged in geophysical research or its applications, elected by the Executive Committee of the American Geophysical Union.

(3) Nationals of other countries having the same qualifications, elected by the Executive Committee of the Union; these may not vote or be officers of the Union or of its Sections, or delegates of the Union to International Assemblies or Meetings.

Members in good standing for a total of 15 years shall, following retirement from active professional service because of age and upon advice to the General Secretary, be extended the complete privileges of members without further payment of dues.

(b) Members ex officio--(1) The Chairmen of the following Divisions of the National Research Council: Foreign Relations; Physical Sciences; Chemistry and Chemical Technology; Geology and Geography; and Biology and Agriculture.

(2) Officers of the International Union of Geodesy and Geophysics and of its Associations, who are citizens of the United States of America.

(c) Corresponding Members--Nationals of other countries, outstanding in the field of geophysics, elected by the Executive Committee of the American Geophysical Union; they shall not pay dues but shall enjoy the privileges of Members except that they may not vote or be officers of the Union or of its Sections or delegates of the Union at International Assemblies or Meetings.

(d) Associates--Citizens of the United States of America other than those eligible for regular membership under Article 3, Sections (a) or (b), whose interest in Geophysics is deemed by the Executive Committee of the Union to warrant their election. Associates shall enjoy the privileges of Members except that they may not be officers of the Union or of the Sections, or be delegates of the Union at International Assemblies or Meetings.

(e) Corporation Members--Corporations and other organizations interested in geophysics, elected by the Executive Committee of the Union. The designated representative of each such organization shall enjoy the privileges of a Member.

Article 4: Sections--The American Geophysical Union shall consist of Sections as follows: (a) Geodesy; (b) Seismology; (c) Meteorology; (d) Terrestrial Magnetism and Electricity; (e) Oceanography; (f) Volcanology; (g) Hydrology; and (h) Tectonophysics.

Members, Corresponding Members, Associates, and Corporation Members shall designate the Section, or Sections, with which they desire to be affiliated. The function of the Sections, in their respective fields, shall be the promotion of the objects of the American Geophysical Union.

Article 5: Officers of the American Geophysical Union--The officers of the American Geophysical Union shall consist of a President, a Vice-President, and a General Secretary, whose terms of office shall expire June 30, 1947, but terms of office effective July 1, 1947, shall be for periods of three years, with the limitation that the President and Vice-President shall not be eligible for immediate reelection; in case any office becomes vacant, the Executive Committee of the Union shall designate a successor in office to complete the term. These officers shall be elected by mail ballot.

There may also be elected, by mail ballot, an Honorary President whose nomination shall be tentatively approved at a meeting of the Executive Committee, followed by a mail ballot of the entire Executive Committee. A confirming vote of three-fourths of those voting shall be required to place the name on the ballot. This office shall be filled only as a special honor for outstanding service to the Union. It shall be for life without payment of dues.

The General Secretary shall act also as Treasurer and shall receive and disburse all dues, grants, and funds otherwise received as authorized by the Executive Committee of the Union; his accounts shall be audited annually by a Committee on Audit.

The Executive Committee of the Union may employ an Executive Secretary, who shall be directly responsible to the General Secretary.

Article 6: Officers of Sections--The officers of each Section of the American Geophysical Union shall consist of a President, a Vice President, and a Secretary, whose eligibility and periods of office shall correspond to those of the Union as indicated under Article 5. These officers shall be elected by mail ballot. In case any office becomes vacant the Executive Committee of the Section concerned shall designate a successor in office to complete the term. The President of each Section shall have the power to appoint, with the right to vote, a representative of the Section to such meetings of the Executive Committee of the Union as he may be unable to attend.

Article 7: Executive Committees--The Executive Committee of the Union shall consist of the President, the Vice President, and the General Secretary of the Union, and of the President or his designated representative and Secretary of each Section of the Union, the last past Presidents of the Union and of the Sections, Chairmen of the Standing Committees of the Union; and, in addition, ex officio, the Honorary President, the Executive Secretary of the Union, those officers of the International Union of Geodesy and Geophysics and of its Associations who are citizens of the United States of America, and the Chairman of each of the following Divisions of the National Research Council: Foreign Relations; Physical Sciences; Chemistry and Chemical Technology; Geology and Geography; and Biology and Agriculture.

This Committee shall have charge of all administrative matters of the American Geophysical Union, and shall be the representative of the Union in its relations with the National Research Council and with the International Union of Geodesy and Geophysics. The Executive Committee of the Union, in consultation with the Sections, shall nominate to the Executive Board of the National Research Council delegates, or representatives, to the Assemblies and Meetings of the International Union of Geodesy and Geophysics and of its Associations, in accordance with the regulations fixed by the International Research Council for the voting power of the United States of America.

There shall be an Executive Committee of each of the Sections of the Union which shall include at least the President, Vice-President, and the Secretary and the last past President of the Section.

Article 8: Annual Meetings--The American Geophysical Union and its Sections shall meet annually at such time and place as may be chosen by the Executive Committee of the Union.

Article 9: Special Meetings--Special meetings of the American Geophysical Union, of any Section or of any group of Sections, and of any Local or Regional Branch may be called by the respective Presidents with the advice of the respective Executive Committees; notification of such meetings must be communicated promptly to the office of the General Secretary of the Union.

Article 10: Branches of the Union--Local or Regional Branches of the Union may be established on the approval of the Executive Committee of the Union. These Branches shall be organized along the general lines of the Union, shall be responsible to the Executive Committee of the Union, and shall duly report their activities through the General Secretary.

Article 11: Publications--The official publication of the Union shall be the Transactions of the American Geophysical Union published under the auspices of the National Research Council of the National Academy of Sciences. Control of matter to be published in the Transactions shall rest in an Editorial and Publication Committee composed of at least one Member from each Section, designated by the Executive Committee of the Section which he represents and appointed by the President of the Union. The General Secretary of the Union shall be ex-officio Chairman and the Executive Secretary of the Union shall be ex-officio Secretary. The Editorial and Publication Committee shall have responsibility (a) of acceptance, editorial revision and condensation, or rejection of any material submitted for publication in the Transactions and (b) as regards any special publications subject to the approval of the Executive Committee of the Union.

Non-members of the Union may subscribe to the Transactions, and purchase individual copies thereof, as well as other publications of the Union at rates approved by the Executive Committee of the Union.

Article 12: By-Laws--The American Geophysical Union is authorized to enact such By-Laws as may be necessary for the performance of its functions and duties.

Article 13: Amendments--(a) Any Member, Associate, or Corporation Member may propose an amendment to the Statutes or By-Laws, which after consideration by the Committee on Statutes and By-Laws and upon approval by the Executive Committee of the Union, shall be submitted for vote to the membership of the Union.

(b) After 30 days' notice has been given, amendments to the Statutes or By-Laws shall be voted on by mail. They require for adoption a majority vote of the membership voting.

(c) Amendments to the Statutes of the American Geophysical Union shall be subject to the approval of the National Research Council.

BY-LAWS

(1) The fiscal year of the American Geophysical Union shall conform to the fiscal year of the National Research Council.

(2) Members of the Union, in classes (a) and (d) of Article 3 of the Statutes, shall pay dues not to exceed $7 for each calendar year, the amount for each year to be fixed by the Executive Committee of the Union; Members of class (e) shall pay dues of $100 for each calendar year; any Member or Associate, on payment of $100 at any time, shall be relieved of further payment of dues.

(3) Standing Committees shall be as follows: Statutes and By-Laws; Membership; Meetings; Nominations; Budget; Audit; and Editorial and Publication.

(4) Special Committees shall be established from time to time, as need arises, to consider special matters approved by the Executive Committee of the Union.

(5) Appointments to Committees of the American Geophysical Union shall be made by the President or President-Elect and appointments shall terminate at the end of the fiscal year for which they are made, unless otherwise specifically designated; no appointment shall extend, however, beyond the term of office of the appointing President or President-Elect.

(6) Meetings of the Union shall be called at least 30 days in advance, and those present at the meeting shall constitute a quorum.

(7) Meetings of the Executive Committee of the Union shall be called by the President at least 15 days in advance and a minimum of 12 shall constitute a quorum.

(8) Final action on matters affecting any Section specifically shall not be taken by the Executive Committee of the Union when that Section is not represented.

(9) Statutes and By-Laws adopted by a Section or Branch shall not conflict with the provisions of the Statutes and By-Laws of the Union.

(10) Matters pertaining solely to a Section and not to the Union as a whole, shall be acted upon by the Section concerned.

(11) No mail ballot of the Union shall be closed until at least 30 days after date of issue.

(12) Officers, designated by the Executive Committee of the Union or the Executive Committee of any of its Sections, to fill uncompleted terms, shall not hold office without election after expiration of the period for which their predecessors were elected.

(13) Removal from the rolls, other than by resignation, of a Member, Corresponding Member, Associate, or Corporation Member of the American Geophysical Union shall be made only upon a three-fourths vote of a quorum of the Executive Committee of the Union; Members, Associates, and Corporation Members who fail to pay dues for two consecutive years shall be reported to the Executive Committee by the General Secretary with recommendation that their names be removed from the Union's rolls.

(14) Under special circumstances and upon request to the General Secretary any Member or Associate may be transferred to an Inactive List of the Union without further payment of dues and without other privileges as Member or Associate but reinstatement may be made upon request and payment of current year's dues.

Reelection of Members and Associates who have been dropped from the rolls by action of the Executive Committee of the Union may be effected only after filing a signed application under the usual procedure for election of Members and Associates.

(15) The Executive Committee of the Union may arrange, either through bequests, special contributions, grants, or other funds of the Union, for awards, medals, honoraria, or certificates of merit to geophysicists in recognition of meritorious work or service in the field of the whole Union or in the field of any of its several Sections, and for scholarships, fellowships, or grants-in-aid to assist worthy candidates in the advancement of geophysical science.

(16) The Executive Committee may appoint Union or Section representatives to other organizations, upon mutual agreement, when such representation may promote coordination and interest in

geophysics. The Executive Committee of the Section concerned shall make tentative arrangements for interorganization-relationships and make selections of representatives of the Sections. Arrangements and commitments must be ratified by the Executive Committee of the Union before they are binding on the Union.

(17) The duties of the President shall be those ordinarily appertaining to this office; he shall preside at the meetings of the Executive Committee and at General Meetings of the Union, shall appoint members of Standing and Special Committees; in the absence or disability of the President, the Vice-President shall carry out the duties ordinarily performed by the President. The more important letters, and especially those concerned with policy of the Union, shall be signed by the President or the General Secretary in accordance with rules, precedents, and decisions of the Executive Committee of the Union.

(18) The General Secretary elected by the Union shall be responsible to the Executive Committee of the Union for the general administration of the Union's activities as determined by the Executive Committee of the Union. He shall exercise general supervision over the Executive Secretary, serve without honorarium, receive and disburse funds for the Union in accordance with the instructions of the Executive Committee of the Union, and provide a surety bond, in a sum set by the Executive Committee of the Union and at the expense of the Union, for funds of the Union in his control. He shall sign checks as General Secretary on the account of the American Geophysical Union with a depository approved by the Executive Committee of the Union; in his absence the President, or, in his absence, the Vice-President, of the Union shall sign checks against the account.

(19) The Executive Secretary shall be responsible to the General Secretary and, with the assistance of such clerical help as is necessary, shall perform all executive and other duties as indicated by the General Secretary.

(20) One copy of each issue of (a) the Transactions, (b) any published List of Members and Officers, and (c) any other publication which may be approved for free distribution to the membership by the Executive Committee of the Union, shall be sent to each Member, Associate, and Corporation Member whose annual dues for the calendar year have been paid by July 1; any person or organization newly elected as Member, Associate, or Corporation Member shall be sent without charge one copy of each of these publications beginning with the calendar year in which elected and for which dues have been paid. Each member on a retired basis, Member ex officio, and Corresponding Member shall be accorded this privilege also.

Each person and organization in good standing in any class of membership may purchase any available publication of the Union at one-third discount from printed price-list to non-members. The General Secretary is authorized to establish discounts for sales of publications in quantity.

AMERICAN
GEOPHYSICAL
UNION

UNSELFISH
COOPERATION
IN RESEARCH

APPENDIX C--OFFICERS OF AMERICAN GEOPHYSICAL UNION SINCE ORGANIZATION IN 1919

(The officers of the Union and of its individual Sections until April 28, 1938, were designated as Chairman, Vice Chairman, and General Secretary (for the whole Union) and Secretary (for Sections); thereafter the designations have been President, Vice President, General Secretary, and Secretary.)

Section	President	Vice President	Secretary
General officers of the Union			
Union	W. Bowie[a] (1920-1922)	L. A. Bauer[a] (1920-1922)	H. O. Wood (1919-1921)
	L. A. Bauer[a] (1922-1924)	A. L. Day (1922-1924)	W. J. Humphreys[a] (1921-1922)
	H. F. Reid[a] (1924-1926)	H. S. Washington[a] (1924-1926)	W. Bowie[a] (1922-1925)
	H. S. Washington[a] (1926-1929)	G. W. Littlehales[a] (1926-1929)	J. A. Fleming (1925-1947)
	W. Bowie[a] (1929-1932)	L. H. Adams (1929-1932)	K. H. Beij (1947-1953)
	W. J. Humphreys[a] (1932-1935)	A. H. Clark (1932-1935)	[Waldo E. Smith Executive Secretary since September, 1944]
	N. H. Heck[a] (1935-1938)	R. M. Field (1935-1938)	
	R. M. Field (1938-1941)	W. C. Lowdermilk (1938-1941)	
	W. C. Lowdermilk (1941-1944)	L. H. Adams (1941-1944)	
	L. H. Adams (1944-1947)	W. H. Bucher (1944-1947)	
	O. E. Meinzer[a] (1947-1948)	H. U. Sverdrup[b] (1947-1948)	
	W. H. Bucher (1948-1953)	F. W. Reichelderfer (1948-1953)	
Officers of the Sections			
(a) Geodesy	W. Bowie[a] (1920-1922)	J. F. Hayford[a] (1920-1922)	H. O. Wood (1920-1922)
	J. F. Hayford[a] (1922-1924)	R. L. Faris[a] (1922-1924)	W. Bowie[a] (1922-1925)
	R. L. Faris[a] (1924-1926)	J. F. Hayford[a] (1924-1925)	W. D. Lambert (1925-1931)
	W. Bowie[a] (1926-1929)	W. Bowie[a] (1925-1926)	C. H. Swick (1931-1937)
	W. D. Lambert (1929-1932)	F. E. Wright[a] (1926-1929)	W. D. Sutcliffe (1937-1943)
	H. G. Avers (1932-1935)	L. J. Briggs (1929-1932)	J. A. Duerksen (1943-1947)
	C. L. Garner (1935-1938)	D. C. Barton[a] (1932-1935)	F. L. Culley (1947-1953)
	C. H. Swick (1938-1941)	P. H. Underwood (1935-1938)	
	R. M. Wilson (1941-1944)	R. M. Wilson (1938-1941)	
	W. D. Sutcliffe (1944-1947)	C. R. Longwell (1941-1944)	
	H. W. Hemple (1947-1950)	P. Kissam (1944-1947)	
	H. H. Hess (1950-1953)	H. H. Hess (1947-1950)	
		A. J Hoskinson (1950-1953)	

(Continued)

APPENDIX C--Continued

Section	President	Vice President	Secretary
Officers of the Sections -- Continued			
(b) Seismology	H. F. Reid[a] (1920-1922)	J. C. Branner[a] (1920-1922)	H. O. Wood (1920-1922)
	W. J. Humphreys[a] (1922-1924)	J. B. Woodworth[a] (1922-1924)	D. L. Hazard[a] (1922-1928)
	J. B. Woodworth[a] (1924-1926)	L. H. Adams (1924-1926)	F. Neumann (1928-1931)
	L. H. Adams (1926-1929)	N. H. Heck[a] (1926-1929)	H. E. McComb[a] (1930-1936)
	N. H. Heck[a] (1929-1932)	F. Wenner (1929-1932)	F. Neumann (1936-1941)
	F. Wenner (1932-1935)	F. W. Lee (1932-1935)	A. Blake (1941-1945)
	F. W. Lee (1935-1938)	J. B. Macelwane (1935-1938)	L. M. Murphy (1945-1947)
	J. B. Macelwane (1938-1941)	H. E. McComb[a] (1938-1941)	Florence Robertson (1947-1950)
	H. E. McComb[a] (1941-1944)	V. C. Stechschulte (1941-1944)	J. T. Wilson (1950-1953)
	V. C. Stechschulte (1944-1947)	F. Neumann (1944-1947)	
	F. Neumann (1947-1950)	P. Byerly (1947-1950)	
	P. Byerly (1950-1953)	L. M. Murphy (1950-1953)	
(c) Meteorology	C. F. Marvin[a] (1920-1922)	W. J. Humphreys[a] (1920-1922)	A. J. Henry[a] (1920-1929)
	E. H. Bowie[a] (1922-1924)	R. DeC. Ward[a] (1922-1924)	O. H. Gish (1929-1935)
	C. G. Abbot (1924-1926)	H. H. Kimball[a] (1924-1926)	H. D. Harradon[a] (1935-1947)
	H. H. Kimball[a] (1926-1929)	G. W. Littlehales[a] (1926-1929)	W. C. Jacobs (1947-1953)
	G. W. Littlehales[a] (1929-1932)	W. R. Gregg[a] (1929-1932)	
	W. R. Gregg[a] (1932-1935)	C. F. Brooks (1932-1935)	
	C. F. Brooks (1935-1938)	R. H. Weightman (1935-1938)	
	R. H. Weightman (1938-1941)	C. W. Thornthwaite (1938-1941)	
	C. W. Thornthwaite (1941-1944)	C.-G. Rossby (1941-1944)	
	F. W. Reichelderfer (1944-1947)	H. R. Byers (1944-1947)	
	H. R. Byers (1947-1950)	B. Holzman (1947-1950)	
	B. Holzman (1950-1953)	H. C. Willett (1950-1953)	
(d) Terrestrial Magnetism and Electricity	L. A. Bauer[a] (1920-1922)	W. F. G. Swann (1920-1922)	J. A. Fleming (1920-1929)
	W. F. G. Swann (1922-1924)	L. A. Bauer[a] (1922-1924)	H. W. Fisk[a] (1929-1932)
	L. A. Bauer[a] (1924-1926)	N. H. Heck[a] (1924-1926)	E. O. Hulburt (1932-1938)
	N. H. Heck[a] (1926-1929)	J. H. Dellinger (1926-1929)	

(Continued)

APPENDIX C--Continued

Section	President	Vice President	Secretary
	Officers of the Sections -- Continued		
(d) Terrestrial Magnetism and Electricity (concluded)	D. L. Hazard[a] (1929-1932)	L. W. Austin[a] (1929-1932)	J. W. Joyce (1938-1944)
	J. A. Fleming (1932-1935)	S. B. Nicholson (1932-1935)	D. G. Knapp (1944-1950)
	O. H. Gish (1935-1938)	T. H. Johnson (1935-1938)	L. R. Alldredge (1950-1953)
	E. O. Hulburt (1938-1941)	E. A. Eckhardt (1938-1941)	
	E. A. Eckhardt (1941-1944)	H. F. Johnston (1941-1944)	
	H. F. Johnston (1944-1947)	Irwin Roman (1944-1947)	
	Irwin Roman (1947-1950)	J. W. Joyce (1947-1950)	
	J. W. Joyce (1950-1953)	V. Vacquier (1950-1953)	
(e) Oceanography	G. W. Littlehales[a] (1920-1922)	A. G. Mayor[a] (1920-1922)	J. T. Watkins (1920)
	J. P. Ault[a] (1922-1924)	G. W. Littlehales[a] (1922-1924)	W. E. Parker (1920-1923)
	N. H. Heck[a] (1924-1926)	W. J. Peters[a] (1924-1926)	G. T. Rude (1923-1926)
	T. W. Vaughan[a] (1926-1928)	G. T. Rude (1926-1928)	A. H. Clark (1926-1929)
	R. L. Faris[a] (1928-1929)	W. J. Peters[a] (1928-1929)	H. A. Marmer[a] (1929-1932)
	(Messrs. Faris and Peters elected at Ninth Annual Meeting to complete terms of officers who resigned because of expected absences from United States during 1929.)		
	A. H. Clark (1929-1932)	H. B. Bigelow (1929-1932)	C. O. Iselin (1932-1935)
	H. A. Marmer[a] (1932-1935)	T. G. Thompson (1932-1935)	P. C. Whitney (1935-1941)
	T. G. Thompson (1935-1938)	C. O. Iselin (1935-1938)	Waldo L. Schmitt (1941-1944)
	C. O. Iselin (1938-1941)	G. F. McEwen (1938-1941)	L. P. Disney (1944-1947)
	P. C. Whitney (1941-1944)	H. U. Sverdrup (1941-1944)	R. H. Fleming (1947-1953)
	H. U. Sverdrup (1944-1947)	Waldo L. Schmitt (1944-1947)	
	G. F. McEwen (1947-1950)	Edw. H. Smith (1947-1950)	
	A. C. Redfield (1950-1953)	R. R. Revelle (1950-1953)	
(f) Volcanology	H. S. Washington[a] (1920-1922)	R. A. Daly (1920-1922)	H. O. Wood (1920-1921)
	L. H. Adams (1922-1924)	T. A. Jaggar, Jr.[a] (1922-1924)	R. B. Sosman (1921-1928)
	T. A. Jaggar, Jr.[a] (1924-1929)	N. L. Bowen (1924-1926)	C. N. Fenner (1928-1932)
	A. L. Day (1929-1932)	F. E. Wright[a] (1926-1929)	A. H. Koschmann (1932-1935)
	C. N. Fenner (1932-1935)	R. A. Daly (1929-1932)	

(Continued)

APPENDIX C--Concluded

Section	President	Vice President	Secretary
Officers of the Sections -- Concluded			
(f) Volcanology (concluded)	E. T. Allen (1935-1938)	E. S. Larsen (1932-1935)	E. Callaghan (1935-1938)
	E. G. Zies (1938-1941)	W. S. Burbank (1935-1938)	J. Gilluly (1938-1940)
	A. F. Buddington (1941-1944)	A. Knopf (1938-1941)	E. Ingerson (1940-1941)
	R. E. Fuller (1944-1947)	J. F. Schairer (1941-1944)	J. S. Vhay (1941-1944)
	W. S. Burbank (1947-1950)	Howel Williams (1944-1947)	F. G. Wells (1944-1950)
	E. S. Larsen, Jr. (1950-1953)	W. F. Foshag (1947-1950)	F. Chayes (1950-1953)
		T. P. Thayer (1950-1953)	
(x) Geophysical Chemistry	A. L. Day (1920-1922)	F. W. Clarke[a] (1920-1922)	R. B. Sosman (1920-1924)
	H. S. Washington[a] (1922-1924)	W. Cross[a] (1922-1924)	
	(Section was discontinued May 31, 1924, as International Union failed to provide for such a Section.)		
(g) Hydrology (Section organized November 15, 1930)	O. E. Meinzer[a] (1930-1933)	R. E. Horton[a] (1930-1933)	H. N. Eaton (1930-1933)
	C. S. Scofield (1933-1936)	C. H. Lee (1933-1936)	K. H. Beij (1933-1947)
	L. K. Sherman (1936-1939)	J. E. Church (1936-1939)	Ray K. Linsley, Jr. (1947-1953)
	N. C. Grover (1939-1942)	M. P. O'Brien (1939-1942)	
	J. E. Church (1942-1947)	L. G. Straub (1942-1947)	
	L. G. Straub (1947-1950)	F. J. Veihmeyer (1947-1950)	
	F. J. Veihmeyer (1950-1953)	M. Bernard[a] (1950-1951)	
		W. B. Langbein (1951-1953)	
(h) Tectonophysics (Section organized April 9, 1940)	L. H. Adams (1940-1943)	R. A. Daly (1940-1943)	D. T. Griggs (1940-1943)
	E. Cloos (1943-1947)	L. L. Nettleton (1943-1947)	M. K. Hubbert (1943-1947)
	M. K. Hubbert (1947-1950)	Robert Balk (1947-1950)	W. S. Burbank (1947-1953)
	Robert Balk (1950-1953)	Francis Birch (1950-1953)	

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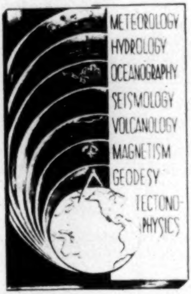
[a] Deceased. [b] Resigned as Vice President, having moved permanently to Norway.

APPENDIX D--DESCRIPTIVE PAMPHLET OF THE AMERICAN GEOPHYSICAL UNION AND OF THE SECTIONS OF THE UNION (AS OF 1952)



THE AMERICAN GEOPHYSICAL UNION

The American Geophysical Union (AGU) was established in 1919 by the National Research Council as the United States Committee of the International Union of Geodesy and Geophysics (IUGG). In this regard it is unique among scientific organizations.

In addition to this international relationship, it is a group of scientists and scientific workers in the broad field of the Earth Sciences. Most of the members are in the United States, with some scattered over the world. The Executive Committee of the Union serves also as the Committee on Geophysics of the National Research Council of the National Academy of Sciences. In this threefold capacity AGU is in excellent position to keep its membership abreast of developments in Geophysics abroad as well as at home.

The objectives of AGU are to promote the study of problems concerned with the figure and physics of the Earth, to initiate and coordinate researches which depend upon national and international cooperation, and to provide for their scientific discussion and publication.

Papers relating to developments in the broad field of Geophysics and its branches are presented and discussed at the annual meetings and regional meetings which are often held in cooperation with other scientific organizations. These and other papers, submitted directly, are published in the bimonthly Transactions which comprise 900 to 1000 pages annually. Transactions also include reviews, bibliographic material, and items of general geophysical interest.

In these critical years greater emphasis than ever before is being placed on science and its relationship to international good will. The IUGG has resumed its functions effectively, as evinced by the Eighth General Assembly held at Oslo, Norway, in 1948, and the Ninth at Brussels, Belgium, in August 1951, and is assuming an important role in relation to the International Council of Scientific Unions, United Nations Educational, Scientific, and Cultural Organization, and scientific activity in general.

Workers in any of the branches or fields of interest outlined below, and those such as engineers, geologists, ecologists, and agriculturalists who have a major interest in any of them, may become members of the AGU, take part in its activities, and receive its publications. To become a member, one should consult a member, or write to the American Geophysical Union, 1530 P Street, N.W., Washington 5, D. C., to secure an application form. Dues for individual members are $7.00 per year, including a subscription to the Transactions. Corporation membership dues are $100 per year. A member may affiliate with as many Sections as he desires without further payment.

THE SECTIONS OF THE UNION

(a) Geodesy

This Section of the Union is devoted to surveying of large areas on the Earth's surface, dealing particularly with triangulation, leveling, and gravimetric surveys. Its objectives are principally determining the shape and size of the Earth and adequate mapping of the Earth's surface. Borderline subjects are photogrammetry and cartography. The fields of interest are:

Shape and size of Earth
Triangulation
Precise leveling
Mapping
Gravimetric surveys and prospecting
Earth tides
Variation of latitude
Deflections of the vertical

(b) Seismology

The Section is of interest to the geophysicist, the geophysical prospector, the foundation engineer, the structural engineer, the geologist, the astronomer, and the insurance executive. The fields of interest are:

Problems of earthquakes
Transmission of vibratory waves through the Earth
Internal constitution of the Earth
Surface structure of the Earth
Seismic exploration

(c) Meteorology

Meteorology is the scientific study of the physical processes which occur in the atmosphere and of the connected processes of the lithosphere and hydrosphere. It seeks to provide an understanding of the causes of weather and climatic conditions and their changes. These exert a profound influence on the entire course of existence of everything on the Earth's surface and in its gaseous envelope of utmost interest and the recent developments in artificial weather control. Meteorology is therefore related and of universal interest to all branches of pure and applied science, technology, agriculture, business, communications and transport, and military and naval strategy and tactics. The fields of interest are:

- Practical meteorology
  - Methods, data, forecast, and other applications
- Physical properties, composition, and general structure of the atmosphere
  - Structure, mechanics, and thermodynamics of the atmosphere in general; radiation and temperature; atmospheric pressure; wind; water vapor and hydrometeors, fog, clouds, and precipitation; soil moisture and hydrology; hydrometeorology
- Climatology
  - Solar climate, climatic zones, influence of latitude; variations of climate; microclimatology; types of climate, bioclimatology; climatology of the free atmosphere; influence of environment
- Various phenomena and influences
  - Cosmic influences; visibility through the atmosphere; optical, electrical, and acoustical phenomena in the atmosphere

(d) Terrestrial Magnetism and Electricity

The field of this Section is the study of the magnetic and electric phenomena of the Earth's interior and atmosphere. The field has experienced new impetus during recent years because of developments in radio communication in which the magnetic and electric properties of the outer atmosphere play a vital role. Cosmic radiation likewise comes into this field. The intimate connection between the electrical and magnetic conditions of the Earth and various solar phenomena has caused many astrophysicists and solar physicists to affiliate with the Section. The fields of interest are:

Magnetic and electric phenomena and properties of the Earth and the atmosphere
Permanent geomagnetic fields; variable fields, internal and external
Natural electric earth currents; earth resistivity
Electric fields of the atmosphere, average and variable aspects
Electrical properties of the atmosphere including the ionosphere
Relations to cosmic phenomena
Isomagnetic and isoelectric charts and applications to navigation, wired and wireless communication, determination of subsurface geology and ore deposits
Airborne magnetic studies

(e) Oceanography

Covering the greater part of the Earth, the sea has a profound effect on man and the world in which he lives. In their interaction with the atmosphere, the oceans exercise a marked influence over climate and vegetation. Present processes of sedimentation help to interpret the geological history of the Earth. The configuration of the ocean bottom, the formation of sea ice, and the action of waves, tides, and currents have an important bearing on coastal and maritime activities. Oceanic movements together with the physical and chemical properties of sea water affect marine life and thereby influence fisheries. The sea thus presents a field of research not only for the oceanographer but also for workers in bordering branches of science. The fields of interest are:

Configuration of oceanic basins
Ocean-bottom deposits, and shore-line processes
Interrelationships between the atmosphere and the surface of the sea
Physical and chemical properties of sea water
Waves, tides, currents, and related phenomena

(f) Volcanology

The Section of Volcanology encourages research not only in "pure" volcanology but also in many fields such as the study of volcanic and intrusive rocks, relation of ore deposits to igneous activity, and laboratory experiments on processes of volcanism and the formation of igneous rocks and ore deposits. Among the fields of interest are:

Origin of igneous rocks
Geochemistry and radioactivity
Volcanic activity and products
Mechanics of intrusion
Petrography
Experimental petrology
Ore-forming fluids and solubility of elements in them

(g) Hydrology

The Section of Hydrology deals with the distribution, behavior, and disposition of precipitation on the land areas of the Earth, and as such is a borderline science of interest to agronomists, engineers, foresters, meteorologists, soils technicians, geologists, and others. It thus forms a meeting ground for all those who are concerned with any phase of hydrology. Since the inception of the Section in 1931, its membership has contributed much to theories of precipitation, runoff, infiltration and percolation, movement of flood waves, soil erosion and the transportation and deposition of sediment, density currents, the behavior of ground water, evapotranspiration, glaciers, the physics of soil moisture, and the development of useful techniques for dealing with hydrologic problems. The fields of interest are:

- Precipitation
- Runoff
- Infiltration and percolation
- Evaporation and transpiration
- Chemistry of natural waters
- Ground water
- Soil moisture
- Dynamics of streams
  - Transportation and deposition of sediment
  - Hydraulics of natural channels
- Lakes
- Glaciers
- Snow and ice, snow surveying
- Permafrost

(h) Tectonophysics

The Section of Tectonophysics coordinates the application of physical methods and geologic and geophysical data to the solution of problems of Earth structure, through laboratory experiments, geological observations, and theoretical analyses. The fields of interest are:

In the laboratory

Physical constants of rocks and minerals
Deformation of minerals, including ice
Deformation of rocks
Structural Petrology

In the field

Metamorphic processes
Nature and behavior of the crust
World-wide tectonic patterns
Mechanics of glacier flow
Forces available for crustal deformation

UNSELFISH
COOPERATION
IN RESEARCH

Proposal forms with information regarding requirements for membership may be secured from the

American Geophysical Union
1530 P Street, Northwest
Washington 5, D. C.

APPENDIX E--THE WILLIAM BOWIE MEDAL AND ITS RECIPIENTS, 1939-1953

In January, 1939, Richard M. Field, then President of the American Geophysical Union, brought to a head an idea he had had for several years as a devoted admirer and younger colleague in research of a most beloved and distinguished aluminus of Trinity College (Hartford, Connecticut), Major (Dr.) William Bowie. Field's plan was for an endowment of a "Bowie Medal" to be awarded by the American Geophysical Union for outstanding achievement in cooperative research, especially when this was accomplished under unusual difficulties. Accordingly President Field sent a letter to the late Dr. Remsen B. Ogilby stating that he thought the Medal could be made possible not only by Bowie's "pet" scientific organization (the American Geophysical Union) for which he did so much, but also by his Alma Mater for which Bowie had such a loyal and warm regard. After consideration of the suggestion, President Ogilby consented to act as Chairman of a Special Committee to canvass for the necessary funds. Meanwhile a suggested design for the proposed Medal had been made by Margaret Fleming Nebeker. [She is the only child of our Honorary President. The design and drawings were made with a nominal honorarium. Many favorable comments have been received regarding the unique and most appropriate design, the motif of the obverse side of which is now used on the cover of the Transactions.--Ed.] The design for the Medal and case are shown by the accompanying reproductions of the original drawings (Fig. 2). The members of the Executive Committee of the Union voted secretly on the suggestion and proposed design early in February, 1939.

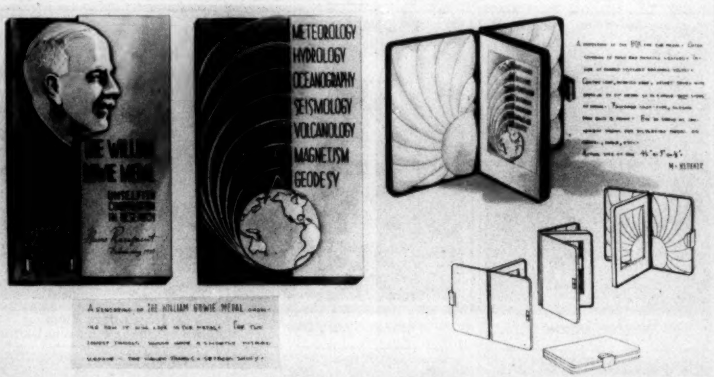


Fig. 2--Reproduction of original drawing for William Bowie Medal and case

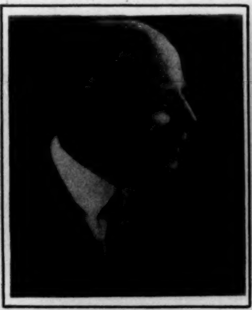
After the unanimous favorable vote of the members of the Executive Committee, an Informal Finance Committee was appointed to seek contributions to endow the Bowie Medal; this Committee consisted of President Ogilby (Trinity College) as Chairman, J. A. Fleming (Carnegie Institution of Washington) as Treasurer, Philip Kissam (Princeton University), H. G. Avers (U. S. Coast and Geodetic Survey), and Richard M. Field (Princeton University). It was not possible for the Committee to inform each of Dr. Bowie's host of friends in an appeal for funds. The Informal Committee solved this difficulty by communications to a selected list of a few of his friends. As a result, 41 friends and coworkers availed themselves of the opportunity of making contributions, individually ranging from $1 to $400. The total amount raised by the Informal Committee for the endowment of the Medal was $738. Fortunately, the cost of the services for the design was most moderate and that for the engraving of the dies by the late B. Basch was less than $200. Thus the cost of the Medal and its preparation for the first 20 awards was met by the original endowment. At the Thirty-Third Annual Meeting it was decided to revert the then small balance in the endowment to the general funds of the Union and, beginning with the award at the Thirty-Fourth Annual Meeting, to absorb the relatively small annual expense in the general expenditures of the Union.

Recipients of the William Bowie Medal, 1939-1952

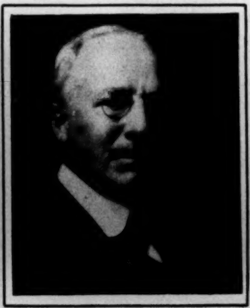
Award	Year	To	Reference in Transactions
1	1939	William Bowie[a]	v. 20, pt. 3, pp. 456-457
2	1940	Arthur Louis Day	v. 21, pt. 2, p. 726
3	1941	John Adam Fleming	v. 22, pt. 2, pp. 234-235
4	1942	Nicholas Hunter Heck[a]	v. 23, pt. 2, pp. 179-180
5	1943	Oscar Edward Meinzer[a]	v. 24, pt. 1, pp. 7-8
6	1944	Henry Bryant Bigelow	v. 25, pt. 2, pp. 214-215
7	1945	Jakob Aall Bonnevie Bjerknes	v. 26, no. 1, pp. 1-2
8	1946	Reginald Alsworth Daly	v. 27, no. 4, pp. 457-458
9	1947	Felix Andries Vening Meinesz	v. 28, no. 3, pp. 359-360
10	1948	James Bernard Macelwane	v. 29, no. 3, pp. 303-305
11	1949	Walter Davis Lambert	v. 30, no. 3, pp. 321-322
12	1950	Leason Heberling Adams	v. 31, no. 3, pp. 341-343
13	1951	Harald Ulrik Sverdrup	v. 32, no. 3, pp. 337-340
14	1952	Harold Jeffreys	v. 33, no. 3, pp. 337-340
15	1953[b]	Beno Gutenberg	v. 34, no. 3, pp. 353-356

[a] Deceased.

[b] Although this report is based on June 30, 1952, it seems appropriate to include the name of the added recipient of this Medal in 1953.--Ed.

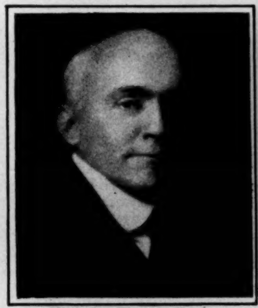


William Bowie

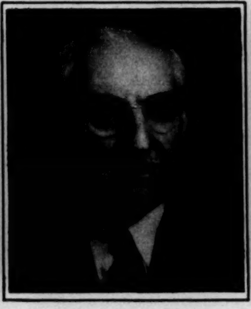


Arthur Louis Day

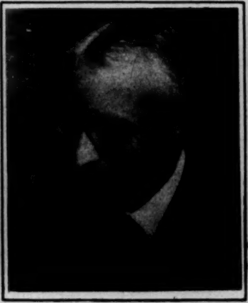
John Adam Fleming
(Photo by Underwood and Underwood)



Nicholas Hunter Heck
(Photo by Harris and Ewing)

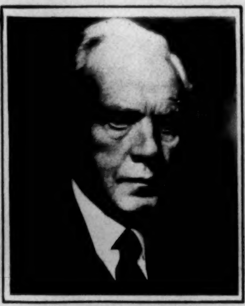


Oscar Edward Meinzer



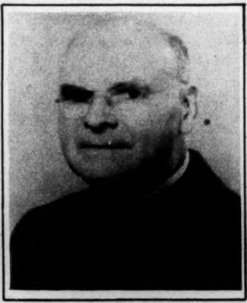
Henry Bryant Bigelow

Jakob Aall Bonnevie Bjerknes

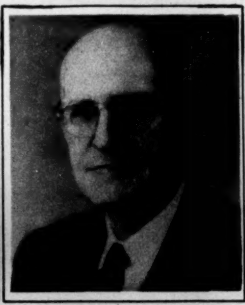


Reginald Alsworth Daly
(Photo by Fabian Bachrach)

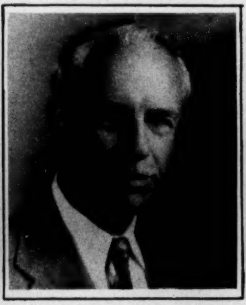
Felix Andries Vening Meinesz



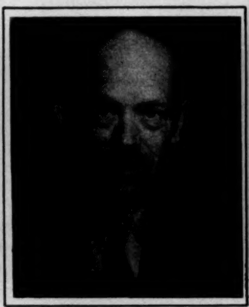
James Bernard Macelwane



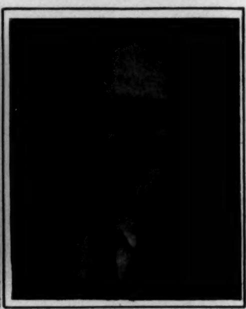
Walter Davis Lambert
(Photo by Harris and Ewing)



Leason Heberling Adams
(Photo by Harris and Ewing)



Harald Ulrik Sverdrup



Harold Jeffreys

Beno Gutenberg

The final vote of the Executive Committee establishing the William Bowie Medal was completed on March 1, 1939. In accordance with the deed of gift, the Medal is to be awarded for distinguished attainment and outstanding contribution to the advancement of cooperative research in fundamental Geophysics. The award has been made annually upon the authorization of the Executive Committee of the Union following recommendation of the Committee on the Award of the William Bowie Medal. The first Medal, struck off by the hydraulic press of the United States Bureau of Engraving through the courtesy of the Director, A. W. Hall, was presented to the late Dr. William Bowie by President Richard M. Field at the General Assembly of the American Geophysical Union on April 28, 1939. In his citation President Field said:

> It is particularly fitting that the first award of this Medal should be made to the man whose name the Medal bears. It is not necessary here, among your intimate friends and colleagues in Geophysics, to refer specifically to your long list of scientific accomplishments and honors. But we do feel that in presenting you with the first imprint of this Medal that has been created in your name, and that of the organization for which you have worked so long and lovingly, we are not handing you a bit of stamped and engraved metal, but rather a powerful talisman of those human forces, affection, esteem, and tradition, so fundamental to the spirit of progress. It is sincerely hoped that in the years to come this Medal through its future awards will continue to promote and recognize that spirit of helpfulness and friendliness in unselfish cooperative research which you have so bountifully displayed.

Fourteen annual awards of the William Bowie Medal were made as indicated in the accompanying tabulation during 1939 through 1952.

When the Section of Tectonophysics was formed in April, 1940, the word "Tectonophysics" was added on the obverse of the Medal; there was ample space for this in the lower right-hand corner. Quite appropriately, the added designation for the new Section is against the crust of the Earth as originally depicted [see reproduction of the new obverse face of the Medal in Appendix D or on the cover of recent issues of the Transactions].

The recent correspondence with Richard M. Field has brought out in his letter of June 18, 1952, some of the thoughts upon which his idea of a William Bowie Medal was based, as follows:

> The idea first occurred to me as a constructive answer to my irritation to the thoughtless behavior of so many colleagues re the Union's Committee on National Welfare and Related Functions. That is why I insisted on the term unselfish cooperation and the concept that the Medal should not be awarded to outstanding geophysicists, as such, but to those who had promoted and used Geophysics in named departments of the Earth sciences other than their regular job or field of research. There is no question but Bowie was outstanding in this unique accomplishment, especially for a federal employee. He not only had splendid imagination but also great skill in getting others to accomplish original cooperative research in the Earth sciences on land, at sea, under the sea, in the air; in fact, the whole Earth, center and circumference. Bowie was a true geonomer, according to S. Chapman's definition. Bowie had the happy and exceedingly clever ability of getting younger men to exceed what they thought was their ability. One worked hard for Bowie but it was lots of fun.

APPENDIX F--BRIEF ACCOUNT OF THE ANNUAL MEETINGS OF THE AMERICAN GEOPHYSICAL UNION AND OF ITS SECTIONS, 1919 THROUGH 1952

The following Notes and table cover the more important details of the 33 Annual Meetings of the Union and of its Sections through 1952. Some of the data given in the table in parentheses are conservatively estimated values.

The paragraphs in the Notes are for individual Annual Meetings, and briefly summarize the high lights of the meetings, with references to symposia and inauguration of new committees bearing on developments in aspects of Geophysics. These Notes include references, which, together with the data of the table, make for a fairly complete account of the evolution of the Union since 1919.

Notes regarding Annual Meetings, 1919-1952

First Annual Meeting - 1920--The meeting was devoted to an Assembly of the Union, at which each Section Chairman presented a paper on Research Problems in Geophysics, with particular reference to his Section. The Constitution was considered in detail and adopted [see Appendix B], and the Secretary, H. O. Wood, outlined the history of the organization and its functions as (1) the American National Committee of the International Union of Geodesy and Geophysics (IUGG) and (2) the American Committee on Geophysics of the National Research Council (NRC). The papers were published also in Proc. Nat. Acad. Sci., v. 6, pp. 545-601, 1920.

Fourth Annual Meeting - 1923--Symposia on (a) Status of Problems in Geophysics, all Sections, and (b) on Hot Springs (Sections of Volcanology and Geophysical Chemistry). The meeting was high lighted by a dinner at the Hotel Lafayette [see Appendix G]. The American delegates reported on the General Assembly of IUGG at Rome in 1922.

Fifth Annual Meeting - 1924--Entire meeting was devoted to discussion and no scientific papers were presented; a mimeographed report was given limited distribution. Section g-1 on Geophysical Chemistry was discontinued on May 31, 1924, as the IUGG had not provided for such a Section.

Sixth Annual Meeting - 1925--Report on General Assembly of IUGG at Madrid in 1924 by American delegates; other delegates reported on the work of four participating Associations at Madrid. Three resolutions were adopted on (1) Regarding Certain Countries as Regards Adhesion to IUGG, (2) Proposed United States Oceanographic Expedition, and (3) Topographic Mapping of the United States.

Seventh Annual Meeting - 1926--Symposia on (a) Constitution of the Earth (Union, five papers) and (b) Scientific Cooperation in the Aleutian Islands (Section f). Five resolutions were adopted on (1) Variation of Latitude, (2) Topographic Mapping of the United States, (3) Greater Uniformity in Pyroheliographic Measurements, (4) Solar Radiation Measurements and Results, and (5) Gravity at Sea.

Eighth Annual Meeting - 1927--Symposia on (a) Current Problems and Developments in Geophysics, (b) Some Factors of Climatic Control (seven papers), (c) Needs and Possibilities of Measurements of Ultra-Violet Light in Solar Spectrum and of the Ozone Content of the High Atmosphere (seven papers), and (d) Correlations of Various Radio Phenomena with Solar and Terrestrial Magnetic and Electric Activities (Section d, ten papers). An unusual number of visitors were present representing various governmental departments and universities and the National Research Council of Canada. Subsequent meetings have been attended by representatives of Canada and Mexico. An exhibit of geophysical instruments, researches, and applications was prepared and displayed April 22-29 in the exhibit rooms of the NAS.

Ninth Annual Meeting - 1928--Symposia on (a) Interrelations between the Sea and Atmosphere and Effect of these Relations on Weather and Climate (Sections c and e, 18 papers), (b) Geophysical Methods as Applied to Geological Structure (Sections a, b, and d, six papers), and (c) Figure of the Earth (Section a, four papers). A special Report on Geophysical Bulletins Covering Scope and General Rulings Concerning Proposed Publication of Bulletins on Geophysical Methods, Instruments, Results, etc., under sponsorship of the Division of Physical Sciences of NRC, and Reports for Sections a, b, c, d, e, and f were made. The papers listed include those by members of National Committees of Canada and Mexico. Nine American delegates reported on the IUGG Assembly at Prague in 1927. It is to be noted that the proposed Bulletins on Geophysical Methods, etc., were later designated Physics of the Earth Series and included ultimately nine substantial volumes

Tabulation of factual data for 33 annual meetings of American Geophysical Union during 1920 to 1952

Annual meeting	Year	Date	Registered attendance	Number of papers in Union and Sections										Place of meetings	Joint meetings	Total number of papers	Membership reported	Reference in NRC Bull. or Union Trans.
				Union	a	b	c	d	e	f	g	g-1	h					
1	1920	Apr 23	25	7	(1)	(1)	(1)	(1)	(1)	(1)	..	(1)	..	BS	U	7	50	NRC Rep. 13, 1920
2	1921	Apr 18-20	(25+)	0	5	0	6	5	6	0	..	0	..	A	..	22	53	NRC Bull. 3, 1922
3	1922	Mar 8	25				Business discussion only							A	U	0	59[i]	Mimeo. only
4	1923	Apr 17-19	(25+)	10Sy8	10	2	6	16	6	Sy7	..	0	..	A,D	fg1	65	65	NRC Bull. 7, 1924
5	1924	May 3	(25+)				Business discussion only							A	U	0	..	Mimeo. only
6	1925	Apr 30-May 1	(35+)	5	8	3	6	7	5	0	..	1	..	A	U	35	..	NRC Bull. 10, 1925
7	1926	Apr 29-30	(45+)	Sy5	11	5	1Sy4	4	8	Sy7	..	0	..	A	U	45	71	NRC Bull. 11, 1926
8	1927	Apr 28-29	75+	1Sy8	7	7	Sy9	Sy11	10	7	..	..	..	A	U	60	72	NRC Bull. 61, 1927
9	1928	Apr 26-27	(75+)	2	6Sy4	Sy6	Sy15	Sy(b)	Sy(c)	5	..	..	..	A	abd,ce	38	75[j]	NRC Bull. 68, 1929
10	1929	Apr 25-26	75	0	8	5	8	Sy7	9	4	..	x	..	A	..	41	95	v. 10-11, 1930
11	1930	May 1-2	(75+)	1Sy6	7	6	7	9	14	3	..	x	..	A,GU	bSE	53	96[k]	v. 10-11, 1930
12	1931	Apr 30-May 1	100	1Sy8	7	12	9	29	11	5	14	x	..	A	U	96	222	v. 12, 1931
13	1932	Apr 28-29	100	Sy9	11	Sy5	11	27	15	3	29	x	..	A,D,ID	U	110	..	v. 13, 1932
14	1933	Apr 27-29	(200)	4Sy9	8	39	11	20	15	5	39	x	..	A,D,ID,GU	U,bSE	150	..	v. 14, 1933
15	1934	Apr 27-28	(250)	10	8	9	12	25	10	11	45	x	..	AB,ID,GU	U,bSE	130	355	v. 15, 1934
16	1935	Apr 25-26	(275)	8Sy9	8	12	13	19	13	14	35	x	..	AB,GU	U,bMSE	131	612	v. 16, 2 pt., 1935
17	1936	Apr 30-May 2	(300)	3Sy4	11	22	9	24	10	9	17Sy39	x	..	AB,GU	U,bSE	148	768	v. 17, 2 pt., 1936
18	1937	Apr 26-30	(350)	3Sy6	13	12	12	24	12	15	40	x	..	AB,GU	U	139	938	v. 18, 2 pt., 1937
19	1938	Apr 27-30	534	Sy6	15	12	6	21	10	12	47	x	..	AB,SI	U	129	1,007	v. 19, 2 pt., 1938
20	1939	Apr 26-29	497	7Sy6	8	1	7	26	8	7	14Sy39	x	..	AB,GW,GU	U	125	1,134	v. 20, 2 pt., 1939
21	1940	Apr 24-27	551	4Sy9	11	15	10	15	8	10	61	x	5	AB	U	148	1,264	v. 21, 1 pt., 1940
22	1941	Apr 30-May 3	479	4PSy21	10	10	10	13	7	11	40	x	12	AB,D,GS	U	140	1,327	v. 22, 3 pt., 1941
23	1942	Apr 3-4	372	1P9	9	4	9	12	8	13	45	x	4	GW	U	115	1,504	v. 23, 2 pt., 1942
24	1943	Apr 23-24	475	3Sy17	7	6	16	8	6	7	49	x	7	GW,GU	U	126	1,898	v. 24, 2 pt., 1943
25	1944	Jun 1-3	496	P13	10	15	28	15	6	4	62	x	8	GW	U,bSE	162	2,151	v. 25, 2 pt., 1944
26	1945	May 31-Jun 1	485	2	10	9	16	12	6	8	19	x	7	GW	U	89	2,445	v. 26, 3 no., 1945
27	1946	May 27-29	710	4	9	10	20	11	11	7	43	x	12	GW	U	127	2,727	v. 27, 6 no., 1946
28	1947	Apr 28-30	764	5P	12	12	10	21	26	8	38	x	6	NM,L,C	U	139	2,966	v. 28, 6 no., 1947
29	1948	Apr 20-22	800	5Sy13	10	8	22	12	10	13	27	x	5Sy6	AB,D,L,NM	U	126	4,290	v. 29, 6 no., 1948
30	1949	Apr 20-22	800	3Sy9	12	11	4Sy6,5	12	10	8	31	x	8Sy3	AB,D,L,NM	U,cb,cd,cM	122	4,449	v. 30, 6 no., 1949
31	1950	May 1-3	865	7P3	10	12	3Sy9	14	21	2Sy6	7Sy4	x	4	AB,L,GS	U,cM	103	4,599	v. 31, 6 no., 1950
32	1951	Apr 30-May 2	1,000	4Sy7	11	10	12	21	17	11	35	x	8	AB,GS	U,cdM	135	4,740	v. 32, 6 no., 1951
33	1952	May 5-7	924+	2	12	7	8Sy6	17	22Sy6	12	41	x	5	AB,GS	U,cd,bM	140	4,775	v. 33, 3 no., 1952

Key to symbols--Place of meeting: AB = Auditorium or Lecture Room, National Academy of Sciences; C = Auditorium, Department of Commerce; D = Root Memorial Hall of Carnegie Institution of Washington; ID = Department of the Interior Building; BS = National Bureau of Standards; NM = National Museum; SI = Smithsonian Institution; GS = Auditorium of General Services Building (formerly Department of Interior); GU = Georgetown University; GW = George Washington University Hall of Government; L = Interdepartmental Auditorium. Other symbols: Sy = Symposium or Symposia; P = Presidential Address; M = American Meteorological Society; S = Social Hour with refreshments; SE = Eastern Section of Seismological Society of America. Parentheses indicate papers presented for Sections at General Union Meetings or estimated entries.

[i] Limit of membership increase authorized to not over 75, excluding ex-officio members.

[j] Limit of membership increased to not over 100, excluding ex-officio members.

[k] Membership made unlimited.

prepared and published during 1931-1942. Of these, two were later reprinted by the offset method to meet orders received after the original editions were exhausted.

Tenth Annual Meeting - 1929--Symposia on (a) Physical Theories of Magnetic and Electric Phenomena (Section d, seven papers), and (b) General Interest Papers on Oceanography (Union, Section e). Two resolutions were adopted on (1) Mapping Situation in the United States and (2) Topography and Control Surveys in the United States. Continued active cooperation between the United States and Canada and Mexico was evidenced by seven papers presented by representatives from Canada and Mexico.

Eleventh Annual Meeting - 1930--Symposium on (a) Utility of Geophysics by Union and an address by Sir Hubert Wilkins on Advisability of Geophysical Investigation in the Arctic by Submarine, and (b) Publication of Earthquake Data (Union, Section b). Section c discussed relations between the IUGG and the International Meteorological Committee (IMC) and heard a final report on the volume on Meteorology in the Physics of the Earth Series regarding Meteorological Units and Instruments. The program of the International Polar Year 1932-33 was discussed in Section d. Three resolutions were adopted on (1) Oceanic Magnetic Survey, (2) Replacement of the Carnegie, and (3) Seismological Stations in South America. At the Union's meeting in 1930 a Section (g) of Hydrology was authorized to conform to the Section of Scientific Hydrology of IUGG. Matters relating to hydrology referred to the American Geophysical Union had previously been looked after by a Special Committee on Hydrology.

Twelfth Annual Meeting - 1931--Symposium on Time Signals (Sections a and b, eight papers). There were numerous progress reports in all Sections as regards the United States, Canada, and Mexico. A report by 14 delegates from the United States to the General Assembly at Stockholm of IUGG was made. Four resolutions were adopted relating to (1) Gravity at Sea, (2) International Cooperation and Study of Tidal Waves, (3) Comparing of Seismological Instruments of the United States and Europe, and (4) Commemoration of the 50th Anniversary of General Greely's Participation in the First International Polar Year of 1882-1883. Section g (Hydrology) was formed November 15, 1930.

Thirteenth Annual Meeting - 1932--Symposia on (a) Application of Geophysics to Ocean Basins and Margins, (b) Applications of Seismology to Ocean Basins (Section (b), and (c) the Second International Polar Year 1932-1933 (Section c). Numerous progress reports in all Sections for the United States, Canada, and Mexico. Six resolutions were adopted relating to (1) Urgent Need of Continuation of Oceanographic Work, (2) Gravity Work at Sea, (3) Apparatus for Gravity Determination at Sea, (4) Naval Observatory Time Signals, (5) Need of Non-Governmental Research Institutions on Meteorology, and (6) Commendation of Geophysical Abstracts published by the United States Bureau of Mines.

Fourteenth Annual Meeting - 1933--Five resolutions related to (1) International Polar Year 1932-1933, (2) Cosmic Rays, (3) Creation of Committee on Snow and Ice, (4) Appropriation for Scientific Investigations by the Federal Government, and (5) Naval Observatory Time Signals. Three sessions of Section b were held jointly with the Eastern Section of the Seismological Society of America. The Union received a report of the Committee on Oceanic Basins. Union had Symposium on Relation of Hydrology to Other Branches of Geophysics (nine papers).

Fifteenth Annual Meeting - 1934--Symposium on Trends in Meteorological Interpretation and Investigation (eight papers). Two resolutions adopted relating to (1) Auroral Observations at College, Alaska, and (2) Carte Bathymétrique Générale des Océans. Four delegates represented the Union at the Fifth General Assembly of IUGG held in Lisbon, 1933. First Regional Meeting was held at Berkeley, California, June 20, 1934, at the University of California with the presentation of 14 papers and in conjunction with the Annual Meeting of the Western Snow Survey Conference, cited previously. The United States Hydrographic Office published a volume of Geophysical Information and Possible Relations to Structural Problems in the West Indies, including results of two submarine expeditions sponsored by the Special Committee of the Union on Geophysical and Geological Study of Oceanic Basins.

Sixteenth Annual Meeting - 1935--Symposium on The Earth's Outer Atmosphere (eight papers). Thirteen resolutions related to (1-3) Vessels for Magnetic and Oceanic Surveys and Data for Bathymetric Charts, (4-6) Data on Geophysics, Geology, and Hydrology Obtained by the Federal Government and Coordination, (7) Recommending Publication of a Manual of Hydrology, (8-10) Establishment of Mountain Stations, Use and Design of Radio Meteorographs, and the Coordination of Snow Surveys in Mountain Regions, and (11-13) Establishment of Additional Seismographic Stations in the United States.

Seventeenth Annual Meeting - 1936--Symposia on (a) Recent Trends in Geophysical Research (Union, four papers), and (b) Ground Water (Section g). Four Special Committees reported on (1) Geophysical and Geological Study of Oceanic Basins, (2) Geophysical and Geological Study of Continents, (3) Establishment of American Journal of Geophysics, and (4) Desirability and Feasibility of Inviting the IUGG to hold its Seventh Triennial General Assembly in Washington in 1939. There was an exhibit prepared by the Committee on Geophysical and Geological Study of Continents. Four resolutions related to National Progress in Geophysics on (1) Topographic Mapping, (2) Naval Observatory Time Signals, (3) Forms for Recording Oceanographic Observations, and (4) Establishment of Hydrographic Surveys. Thirty American delegates indicated for attendance at the Sixth Triennial Assembly of IUGG to be held at Edinburgh in 1936.

Eighteenth Annual Meeting - 1937--Symposium by Section g was devoted to discussion of the General Assembly at Edinburgh and that scheduled for Washington in 1939. Fifty-one members attended and reported on the Sixth General Assembly in 1936 of IUGG at Edinburgh, Scotland. The Committee on Geophysical and Geological Study of Oceanic Basins reported completion on January 15, 1937, of expedition sponsored by the Committee in cooperation with the United States Navy, United States Coast and Geodetic Survey, the Bell Telephone Laboratories, and the American Philosophical Society. The first paid assistant clerk since 1932 for the Union was approved. Invitation for the Seventh General Assembly of IUGG for Washington was accepted at Edinburgh. As a result largely of the Union's Special Committee, the IUGG at Edinburgh established an International Commission on Geophysical and Geological Study of Oceanic Basins.

Nineteenth Annual Meeting - 1938--Symposium on (a) Physics of Volcanic Processes (Union, five papers), and (b) Discussion of Ways and Other Details for the Seventh General Assembly of the IUGG during September, 1939, at Washington. Four resolutions were adopted relating to (1) Magnetic Survey of Land and Water Areas of the United States, (2) Geophysical Survey of the Central Atlantic States, (3) Location of Meteorological Observatories, and (4) Meteorological Research Projects.

Twentieth Annual Meeting - 1939--Symposium on (a) Geophysical Prospecting (Union), and (b) Importance of Geophysics on Study of Continental Borders (nine papers). The first Award of the William Bowie Medal was made at the meeting on April 28, 1939, to William Bowie. This Medal was established by action of the Executive Committee on March 1, 1939 (see Appendix E). Five resolutions were adopted relating to (1) Long-Range Weather Forecasting, (2) Geophysical and Geological Study of Oceanic Basins, (3) Geophysical and Geological Study of Continents, (4) Seismic Activities of the Eastern Section of the Seismological Society of America, and (5) Naval Observatory Time Signals. Arrangements were completed for the Seventh General Assembly of IUGG to be held during September, 1939, at Washington. An important Regional Meeting, cited earlier, was held at Richmond, Virginia, on December 27, 1938, by the Union with Sections D (Astronomy) and E (Geology and Geography) of the American Association for the Advancement of Science in a Symposium on Importance of Geophysics to the Study of Continental Borders (nine papers).

Twenty-First Annual Meeting - 1940--Section h on Tectonophysics was established on April 9, 1940, for the purpose of promoting and encouraging research of fundamental importance to knowledge of Earth structure not covered by any of the other Sections of the Union (five papers and extended discussion, Section h). Five delegates were designated to represent the Union at the Sixth Pacific Science Congress at Berkeley and Stanford University, July 24-August 12, 1939. Six resolutions dealt with (1) Depositories for Geophysical Records, (2) Compilation and Investigation of Sounding Data, (3) Seismic Stations in the North Atlantic, (4) Seward Extension of Submarine Valleys, (5) Analysis and Publication of Data on Rainfall and Runoff, and (6) Naval Observatory Time Signals.

Twenty-Second Annual Meeting - 1941--Presidential address by R. M. Field on Geophysics and World Affairs--A Plea for Geoscience, was delivered in Elihu Root Hall of the Carnegie Institution of Washington. Symposium on (a) Dynamics of Land Erosion (Union, five papers with extensive discussion), and (b) Mechanics of Crustal Flow and Deformation (Section h, 12 papers). Three resolutions dealt with More Adequate Meteorological, Bibliographical and Abstract Services.

Twenty-Third Annual Meeting - 1942--The presidential remarks upon the Award of the Bowie Medal were followed by an address on Recent Explorations in the Mountains and Glaciers of Alaska by B. Washburn and a reception. A Special Committee on National Welfare and Related Functions was set up.

Twenty-Fourth Annual Meeting - 1943--Union's assembly in Hall of Government of George Washington University on the evening of April 24, 1943, included (a) Fifth Award of the Bowie Medal, (b) Memorial Addresses on Recently Deceased Members, David Grosh Thompson, Richard Carlysle Cady, and Max Harrison Demorest, and (c) three conferences on the Present Tentative Program of the Commission on Continents and Oceanic Structure of the IUGG, led by Chairman R. M. Field, and followed by an active discussion by more than 20 members. Eight resolutions were adopted on (1) Precise Magnetic Surveys and Mapping, (2) Essential Geophysical Observations for Duration of the War, (3) Implementation of Meteorology for War Purposes, (4) Establishment of More Stations in Oceanic Areas and Antarctica in Interest of Daily and Long-Range Forecasting, (5) Naval Time-Signal Surveys, (6) Adequate Post-War Program on Seismological Investigations, (7) Practical Post-War Program in all Branches of Geophysics, and (8) Ways and Means of Providing Employment for Geophysicists Released from War Effort during Transition from War to Peace. A progress report was submitted by the Special Committee on Establishment of an American Journal of Geophysics.

Twenty-Fifth Annual Meeting - 1944--Seven resolutions were adopted on (1) Post-War Work in Geophysics, (2) Proposed Oceanographic Work by United States Hydrographic Office, (3) Establishment of a Geophysical Station at the University of Alaska, (4) Investigation of Microseismic Phenomena, (5) Accurate Time Signals, (6) Cooperation between Nations of the Western Hemisphere in Seismology, and (7) Thanks to Major P. W. Rainier for his Account of his Effective Work in Supplying Water Supplies for the British Eighth Army in the North African Campaign. The presidential address by Walter C. Lowdermilk, Down to Earth, was followed by the Sixth Award of the Bowie Medal and Major Rainier's account. The final report of the Special Committees on Policy [Trans. 1944, pp. 339-340] and on Finance [Trans. 1944, pp. 344-348] was accepted and the Executive Committee instructed to proceed in 1945 with bimonthly publications of the Transactions. The Special Committee on Finance raised $10,019 from 706 contributions by members and friends of the Union as required by the action of the Rockefeller Foundation in its grant of $20,000 payable during July 1, 1944-June 30, 1947. A Special Committee on Precise Surveys and Mapping was set up. An extensive report was received and approved for plans to begin bimonthly issues of the Transactions with Volume 46 consisting of three numbers for August, October, and December, 1945. An extensive report from the Special Committee on National Welfare and Relations was received and approved (Trans. 1944, pp. 349-365). The Union attained its 25th year in 1944 and in the quarter century did much to advance Geophysics, nationally and internationally, not only as a first-order science but as the foundation of economic applications which will be increasingly valuable in the post-war period.

Twenty-Sixth Annual Meeting - 1945--Eight resolutions were adopted on (1) Cooperation between Nations in Inter-Continental Connection of Geodetic Map-Control Systems, (2) Mapping by the United States Coast and Geodetic Survey and the United States Geological Survey, (3) Suggested Federal Map Information and Distribution Office, (4) Post-War Interdepartmental Map Board, (5) Time-Signal Service, (6) Preparation of Accurate Topographic Maps in Seismic Areas, (7) Seismic Time-Signal Services, and (8) Improved Meteorological Bibliographical Service. A tabulation of educational institutions offering courses in fields of Geophysics was prepared (Trans. 1945, v. 26, pp. 463-476).

Twenty-Seventh Annual Meeting - 1946--Four resolutions were adopted on (1) Availability of Climatological Data, (2) Collection of Hemisphere-Wide Weather Reports, (3) Continuation of Association of Geodesy in IUGG, (4) Time-Signal Service. A group of members was authorized to establish a Tennessee Valley Branch at the Assembly of the Union, following the Award of the Bowie Medal. There was colored motion film on Parícutin Volcano. A supplementary list of educational institutions offering courses in fields of Geophysics was prepared [Trans. 1946, v. 27, pp. 614-617].

Twenty-Eighth Annual Meeting - 1947--Four resolutions were adopted relating to (1) Time-Signal Service, (2) Use of Metric System, (3) Ground-Water Studies of the Geological Survey, and (4) Operation Crossroads. The presidential address by L. H. Adams on the evening of April 2 was on Some Unsolved Problems of Geophysics.

Twenty-Ninth Annual Meeting - 1948--Symposium on The Crust of the Earth (Union, 13 papers). The Union's Assembly Meeting on the evening of April 21 was followed by a lecture by Commander and Mrs. Finn Ronne on their 15-month expedition in Antarctica. Six resolutions were adopted relating to (1) Time-Signal Service, (2) Navy Seismological Stations, (3) Extension of Gravimetric Net, (4) Appreciation of Ronne Expedition for Seismographic Station in Antarctica, (5) Measurement of Gravity at Sea, and (6) Geophysical Data of Commercial Companies.

Thirtieth Annual Meeting - 1949--Symposium on Turbulence and Mixing in the Sea -- Interaction between the Ocean and the Atmosphere (Union, four papers at first session and five at second session and extensive discussion). Report on Eighth General Assembly at Oslo, Norway, August 19-28, 1948, was made by the United States delegates; this was the first post-war Assembly of IUGG. Five resolutions were adopted relating to (1) Communications Services, (2) Time-Signal Service, (3) Measurement of Gravity at Sea, (4) Gravimetric Values in South America, and (5) Extension of Gravimetric Net.

Thirty-First Annual Meeting - 1950--Four resolutions were adopted relating to (1) Communications Services, (2) Time-Signal Service, (3) Antarctic Seismological Station, and (4) Naval Seismological Stations. The presidential address by W. H. Bucher was on Megatectonics and Geophysics, followed by Award of the Bowie Medal at the evening session on May 1.

Thirty-Second Annual Meeting - 1951--Four resolutions adopted on (1) Communications Services, (2) Time-Signal Service, (3) "World Days" or "International Days," and (4) Establishment of Standard Upper Atmosphere Nomenclature. There was also a discussion of a proposed resolution on the International Polar Year, 1957-1958 (to be renamed International Geophysical Year) received from Section d, but action on the resolution was postponed pending further consideration of advisability by the Union of such an International Geophysical Year. Symposium on evening of April 30 on Measurement of Geologic Time, followed by the Bowie Medal Award received on behalf of Harald Ulrik Sverdrup by the Cultural Attaché of the Norwegian Embassy.

Thirty-Third Annual Meeting - 1952--Four resolutions were adopted relating to (1) Appreciation of Cooperation with Officers of Foreign Service of the United States and the Foreign Service Operations Staff of International Trade for Making Available Special Transmission Facilities for Teleseismic Data to the United States Coast and Geodetic Survey, (2) Communications Services, (3) Time-Signal Service, and (4) Increased Financial Support of International Unions. Union lectures on Origin of the Elements by R. A. Alpher and R. C. Herman, and Experimental and Theoretical Operations Research--Its Applications in Combat, Industry, and Science by E. A. Johnson. Symposium on The Upper Atmosphere (eight papers) jointly between Section c and American Meteorological Society. Round-table discussion in Section e on Oceanography. Bowie Medal Award on behalf of Professor Harold Jeffreys through the First Secretary and Educational Officer of the British Embassy. The American delegates to the Brussels Assembly in 1951 of IUGG gave a report on that Assembly.

APPENDIX G--SOCIAL FUNCTIONS AND ACKNOWLEDGMENTS

The Union, from its beginning, has featured at its Annual Meetings and at the Triennial General Assemblies of the International Union of Geodesy and Geophysics and the separate Associations thereof, social gatherings during the scientific programs to promote free and social relations between those in attendance.

So far as the Annual Meetings are concerned, these in recent years have taken the form generally of smokers, usually at the Cosmos Club in Washington. In connection with the earlier years and with regional meetings, these have usually been lucheons and dinners.

An early example was the dinner held in Washington during the Annual Meeting of 1923 and is indicated by the menu reproduced on the next page.

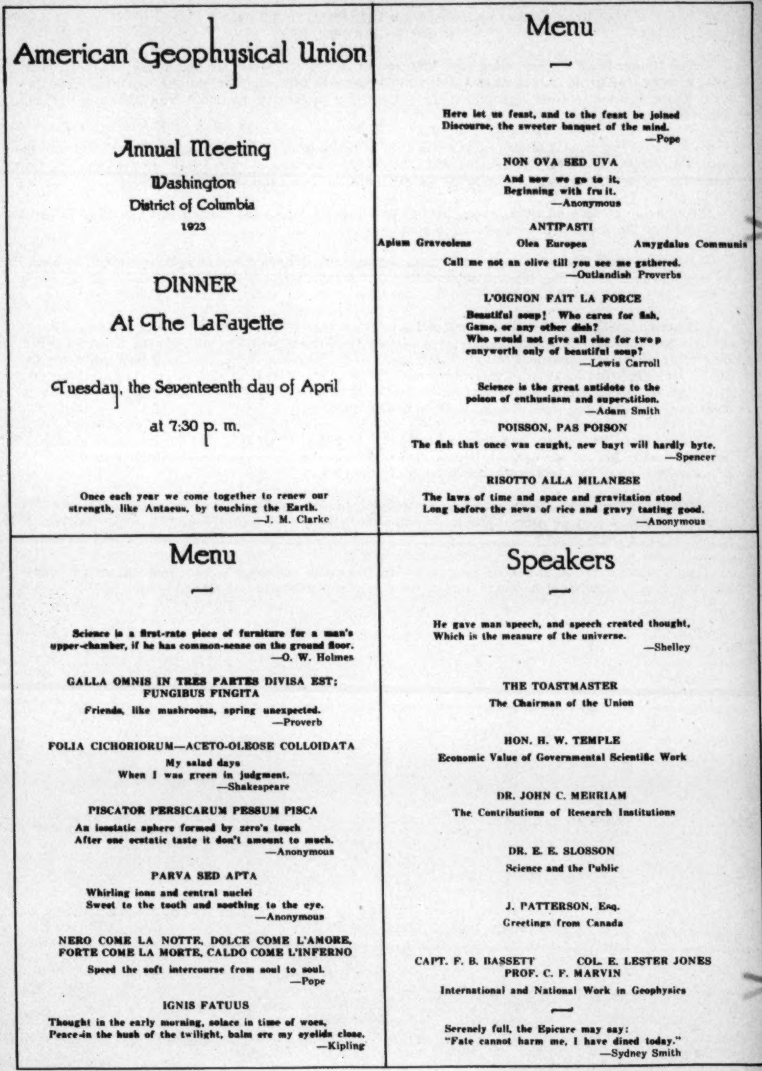
In some cases, these contacts have been strengthened through the mingling at exhibits such as those prepared for the General Assemblies of the International Union of Geodesy and Geophysics (see Appendix K), showing geophysical developments and progress in the United States.

It may be recalled that upon numerous occasions the Union has been privileged to use the facilities of the George Washington University for its Annual Meetings and for the Ninth General Assembly of the International Union of Geodesy and Geophysics which was held in Washington in 1939. Grateful appreciation of this generous courtesy has been indicated in resolutions adopted at the Annual Meetings of the Union and at the General Assembly of IUGG and addressed to the Board of Trustees and to President Marvin of the University.

Georgetown University has also extended the privilege of using its facilities, particularly during several Annual Meetings for joint meetings between the Section of Seismology and the Eastern Section of the Seismological Society of America.

The U. S. Geological Survey, through the Department of the Interior, has made available meeting places for many Annual Meetings and particularly during the Seventh General Assembly of the IUGG in 1939.

Acknowledgment of numerous courtesies during many meetings and for general office quarters for many years must be made also to the Carnegie Institution of Washington.



American Geophysical Union

Annual Meeting

Washington
District of Columbia
1923

DINNER

At The LaFayette

Tuesday, the Seventeenth day of April

at 7:30 p. m.

Once each year we come together to renew our strength, like Antaeus, by touching the Earth.
—J. M. Clarke

Menu

Here let us feast, and to the feast be joined
Discourse, the sweeter banquet of the mind.
—Pope

NON OVA SED UVA

And now we go to it,
Beginning with fruit.
—Anonymous

ANTIPASTI

Apium Graveolens Olea Europea Amygdalus Communis

Call me not an olive till you see me gathered.
—Outlandish Proverbs

L'OIGNON FAIT LA FORCE

Beautiful soup! Who cares for fish,
Game, or any other dish?
Who would not give all else for two p
ennyworth only of beautiful soup?
—Lewis Carroll

Science is the great antidote to the poison of enthusiasm and superstition.
—Adam Smith

POISSON, PAS POISON

The fish that once was caught, new bayt will hardly byte.
—Spencer

RISOTTO ALLA MILANESE

The laws of time and space and gravitation stood
Long before the news of rice and gravy tasting good.
—Anonymous

Menu

Science is a first-rate piece of furniture for a man's upper-chamber, if he has common-sense on the ground floor.
—O. W. Holmes

GALLA OMNIS IN TRES PARTES DIVISA EST;
FUNGIBUS FINGITA

Friends, like mushrooms, spring unexpected.
—Proverb

FOLIA CICHORIORUM—ACETO-OLEOSE COLLOIDATA

My salad days
When I was green in judgment.
—Shakespeare

PISCATOR PERSICARUM PESSUM PISCA

An isostatic sphere formed by zero's touch
After one ecstatic taste it don't amount to much.
—Anonymous

PARVA SED APTA

Whirling ions and central nuclei
Sweet to the tooth and soothing to the eye.
—Anonymous

NERO COME LA NOTTE, DOLCE COME L'AMORE,
FORTE COME LA MORTE, CALDO COME L'INFERNO

Speed the soft intercourse from soul to soul.
—Pope

IGNIS FATUUS

Thought in the early morning, solace in time of woes,
Peace in the hush of the twilight, balm ere my eyelids close.
—Kipling

Speakers

He gave man speech, and speech created thought,
Which is the measure of the universe.
—Shelley

THE TOASTMASTER
The Chairman of the Union

HON. H. W. TEMPLE
Economic Value of Governmental Scientific Work

DR. JOHN C. MERRIAM
The Contributions of Research Institutions

DR. E. E. SLOSSON
Science and the Public

J. PATTERSON, Esq.
Greetings from Canada

CAPT. F. B. BASSETT COL. E. LESTER JONES
PROF. C. F. MARVIN
International and National Work in Geophysics

Serenely full, the Epicure may say:
"Fate cannot harm me, I have dined today."
—Sydney Smith

APPENDIX H--SUMMARY OF RECEIPTS AND DISBURSEMENTS, AMERICAN GEOPHYSICAL UNION, 1919 TO JUNE 30, 1952

During the years 1919 through 1931 funds required for the functioning of the Union, including publication, were provided by the National Research Council. During these years the annual grants of the Council for maintenance expenses varied from $200 to $1,000. Besides these the Council supplied also about $7,600 for publishing some 1,250 pages of seven volumes of Transactions and one special report entitled Survey of Research Problems, and in addition the part-time salaries of a General Secretary and a Stenographer. Detailed statements of totals contributed by the Council were not available to the author.

With the rapid growth and influence of the Union and the reduction in National Research Council funds because of the depression, the National Research Council asked that annual contributions be made by each member beginning in 1932 ($2 from 1932, $3 from 1937, $5 from 1946, and $7 since 1950. Thereafter the total annual grant from the Council averaged about $400. From April, 1932, through June, 1952, the total of annual contributions by members (regular, associate, and corporation) was $207,429.96, sales of publications yielded $76,564.86, contributions for special purposes other than those for the Seventh General Assembly of the International Union of Geodesy and Geophysics in 1939 (see Appendix K) amounted to $29,016.70, grants from the National Research Council aggregated $8,393.48, and other contributions made a grand total of $341,990.49. Among the special grants received there should be noted those of the Rockefeller Corporation of $20,000 in total during 1945-1947 and of the Geological Society of America of $3,000 in 1948.

During the same interval the publication of the Transactions (11,053 pages through 1944 and 6,126 pages since 1945, all, except for 929 pages in letter press of Bulletins published by the National Research Council, printed by the offset method from master copy (prepared on a variable-spacing electric typewriter in book type since 1942) made a total of 17,179 pages equivalent to at least 25,000 pages in letter-press format. The Transactions and Bibliography of Hydrology, United States of America (400 pages) and of reprints and other publications cost $148,476.27. The cost of maintaining paid personnel (now three clerical assistants and an Executive Secretary) since 1932 was $119,571.18. Previously practically all services had been gratuitous. Other expenses included stationery ($9,601.06), meetings ($7,155.78), office equipment ($3,383.29), and postage and communications ($17,619.32). These with other disbursements, as shown in detail by the attached summary (Table 1) and detailed statements of receipts and disbursements, 1932 to 1952 (Tables 2 and 3), make a total of $318,495.36.

Table 1--Summary of American Geophysical Union accounts from April, 1932, to June 30, 1952[a]

Period	Receipts	Disbursements	Accumulated cash balance
April, 1932-Dec. 31, 1936	$ 14,488.35	$ 13,282.76	$ 1,205.59
Jan. 1, 1937-Dec. 31, 1941	41,784.62	36,981.87	6,008.34
Jan. 1, 1942-June 30, 1946	70,829.04	63,389.97	13,447.41
July 1, 1946-June 30, 1952	214,888.48	204,840.76	23,495.13
Totals	$341,990.49	$318,495.36	
Permanent Fund		7,291.06[b]	$23,495.13
Cash Reserve, June 30, 1952		16,204.07	
Check total		$341,990.49	

[a] Corrected for minor bookkeeping errors, 1943-1945.

[b] The Permanent Fund on June 30, 1952, consisted of Series E United States Bonds bought in fiscal year 1946-1947, $1,850.00, and in fiscal year 1947-1948, $518.00, at a total cost of $2,368.00 (maturity value if held for 12 years would be $3,200.00); deposits with Northwestern Federal Savings and Loan Association of $400.00 in fiscal year 1948-1949, $310.00 in fiscal year 1949-1950, $340.00 in fiscal year 1950-1951, and $3,758.75 in fiscal year 1951-1952, a total, including interest of $114.31 to June 30, 1952, of $4,923.06.

[c] See Transactions, v. 33, p. 941, Dec. 1952.

Thus for the fiscal year ended June 30, 1952, there was a Cash Reserve of $16,204.07 available against maintenance and publication from July, 1952; there was also a Permanent Fund of $7,291.06. By the testament of Robert E. Horton the Union, upon the demise of several beneficiaries, will receive a bequest of value estimated around $200,000. The contributions from members, sales, miscellaneous receipts, and interest for the fiscal year ending June 30, 1953, are estimated at $41,250, with expenditures estimated at $40,650. [For summary of, and comments on, receipts ($18,326.61) and disbursements ($15,069.71) by the Union for the Seventh General Assembly of the International Union of Geodesy and Geophysics during 1939 at Washington, see Appendix K.]

The satisfactory publication program (see list of publications in Appendix J) of the Union since 1919 resulted primarily from economical methods of offset publication which, with study of methods in preparing master copy for direct reproduction, have reduced the total average cost per page (for editions ranging from 1,000 in earlier years to 5,600 as the membership and distribution increased) to less than three-quarters that of the conventional form of publication by letter press; indeed, on a strictly comparable basis of actual content of page of Transactions, the total cost per page may be only one-half as much.

Table 2--Summary of

Calendar or fiscal year	Annual contributions	Donations and grants	Grant NRC	Bowie Medal	Publications	Special funds	Services	Washington Assembly IUGG
1932	$ 532.00	......	$ 561.43	.....	$ 757.36	......	......	......
1933	670.00	$ 538.76	557.66	.....	754.37	......	......	......
1934	1,158.00	979.12	375.39	.....	1,073.84	......	......	......
1935	1,408.00	358.40	400.00	.....	967.28	......	......	......
1936	1,653.00	212.57	400.00	.....	1,131.17	......	......	......
1937	1,874.00	393.25	400.00	.....	1,409.29	$1,500.00[e]	......	......
1938	2,933.60	591.50	400.00	.....	2,008.69	......	......	......
1939	3,584.00	433.48	400.00	$738.00	2,979.29	......	$ 500.99[f]	$3,256.90
1940	3,821.00	......	400.00	.....	3,930.21	......	1,084.58[g]	......
1941	4,144.50	......	400.00	.....	4,461.68	135.00	......	......
1942	4,748.00	4.00	102.43	.....	1,652.26	102.00	......	......
1943	5,994.00	......	397.57	.....	2,082.22	2,655.00	......	......
1944[b]	5,408.00	......	167.46	.....	2,245.81	2,080.00	......	......
1945[c]	7,316.33	......	632.04	.....	3,384.81	154.13	......	......
1945-46	13,312.78	......	400.00	.....	4,951.42	......	......	......
1946-47	14,470.89	......	400.00	.....	4,800.68	......	......	......
1947-48	22,265.67	......	400.00	.....	5,593.82	......	......	......
1948-49	21,293.89	......	400.00	.....	4,649.55	......	......	......
1949-50	28,966.90	......	400.00	.....	7,444.26	......	......	......
1950-51	29,877.89	191.93	400.00	.....	7,837.05	......	......	......
1951-52[d]	31,997.51	313.69	400.00	.....	12,449.80	......	......	......
Totals	$207,429.96	$4,016.70	$8,393.98	$738.00	$76,564.86	$6,626.13	$1,585.57	$3,256.90

[a] Transfer to Permanent Fund and not included in totals. [b] January 1 to June 30, 1944. [c] July 1, 1944 to June 30, 1945. [d] To June 30, 1952. [e] Special scholarship fund. [f] $244.88 of this is refund. [g] Refund.

Table 3--Summary of

Calendar or fiscal year	Services	Publications	Meetings	Stationery	Postage, communications	Equipment	Scholarship
1932	$ 119.49	$ 1,317.58	......	$ 18.61	$ 148.94	......	......
1933	221.19	1,788.72	$ 112.00	15.41	175.10	......	......
1934	317.86	2,726.50	132.50	46.16	261.10	......	......
1935	341.92	1,836.06	177.10	81.93	275.04	......	......
1936	350.70	2,137.93	184.34	85.36	410.86	......	......
1937	571.09	3,079.10	209.27	109.56	465.96	$ 100.31	$ 625.00
1938	1,048.25	3,321.18	120.52	163.34	363.59	190.80	875.00
1939	1,270.08	3,840.97	149.20	191.26	516.54	......	......
1940	1,553.15	6,452.42	218.82	177.53	757.94	71.18	......
1941	1,705.29	5,437.71	386.78	220.20	582.73	......	......
1942	2,188.31	2,064.63	419.13	250.63	552.41	16.20	......
1943	2,021.27	4,064.16	260.72	338.75	733.03	......	......
1944[a]	1,627.64	5,006.77	419.90	177.67	638.03	......	......
1945[b]	10,706.19	7,757.67	385.10	830.61	1,052.60	373.27	......
1945-46	10,842.47	8,145.15	378.22	863.57	842.57	3.70	......
1946-47	11,859.11	9,561.48	339.08	1,104.60	918.82	495.83	......
1947-48	16,742.35	11,747.38	584.27	1,545.67	1,165.89	552.00	......
1948-49	15,597.29	12,338.91	427.40	885.47	1,938.61	725.40	......
1949-50	12,062.12	16,953.18	669.22	743.62	2,055.19	307.22	......
1950-51	14,281.16	17,921.21	835.14	915.20	1,828.27	307.72	......
1952[c]	14,144.25	20,977.56	747.07	835.91	1,936.10	239.66	......
Totals	$119,571.18	$148,476.27	$7,155.78	$9,601.06	$17,619.32	$3,383.29	$1,500.00

[a] January 1 to June 30, 1944. [b] July 1, 1944 to June 30, 1945. [c] To June 30, 1952. [d] These are not included in totals for 1932-1952. [e] $244.88 of this is refund. [f] Refund.

receipts, 1932-1952

Miscellaneous	Horton Fund	RF and GSA	Interest	RDB contract	Bibl. of Hydrology 1941-50	Transfer to Permanent Fund[a]	Annual totals
.....	......	......	.....	......	......	......	$ 1,850.79
.....	......	......	.....	......	......	......	2,520.79
.....	......	......	.....	......	......	......	3,586.35
.....	......	......	.....	......	......	......	3,133.68
.....	......	......	.....	......	......	......	3,396.74
$ 0.10	......	......	.....	......	......	......	5,576.64
1.10	......	......	.....	......	......	......	5,934.89
0.66	......	......	.....	......	......	......	11,893.32
2.70	......	......	.....	......	......	......	9,238.49
0.10	......	......	.....	......	......	......	9,141.28
34.73	......	......	.....	......	......	......	6,643.42
3.10	......	......	.....	......	......	......	11,131.89
0.95	......	......	.....	......	......	......	9,902.22
.....	......	$ 6,000.00[h]	.....	......	......	......	17,487.31
.....	......	7,000.00[h]	.....	......	......	......	25,664.20
8.72	$5,000.00	7,000.00[h]	.....	......	......	($1,850.00)	31,680.29
35.73	......	3,000.00[i]	.....	$1,250.00	......	(518.00)	32,545.22
65.93	......	......	.....	1,250.00	......	(400.00)	27,659.37
.....	......	......	$ 14.73	......	......	(310.00)	36,825.89
.....	......	......	37.09	......	......	(340.00)	38,343.96
.....	......	......	62.49	......	$2,610.26	(3,758.75)	47,833.75
$153.82	$5,000.00	$23,000.00	$114.31	$2,500.00	$2,610.26	($7,176.75)[a]	$341,990.49

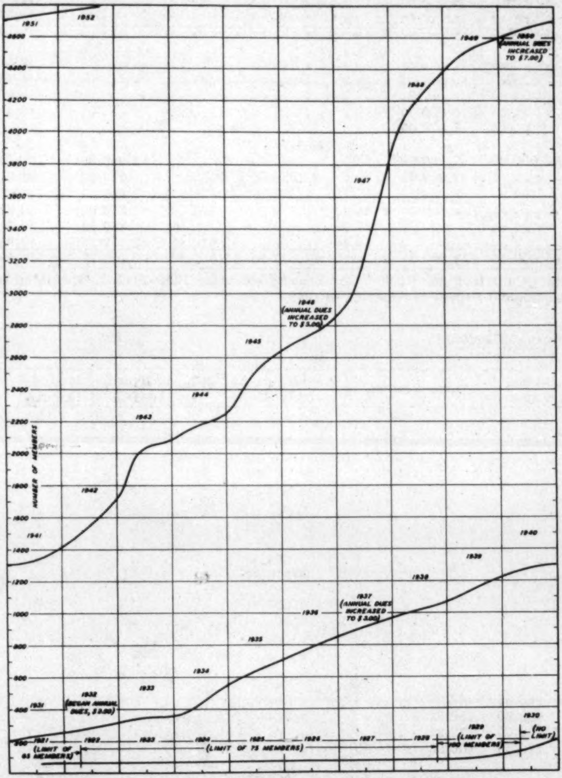
[h] Special grants from the Rockefeller Foundation during 1945-1947. [i] Special grant from the Geological Survey of America in 1948.

disbursements, 1932-1952

Bowie Medal	Horton Fund	Travel	Interest	Washington Assembly, IUGG	Bibl. of Hydrology, 1941-50	Miscellaneous	Annual totals
.....	......	.....	.....	......	......	$ 0.36	$ 1,604.98
.....	......	.....	.....	......	......	.....	2,312.42
.....	......	.....	.....	......	......	.....	3,484.12
.....	......	.....	.....	......	......	.....	2,712.05
.....	......	.....	.....	......	......	.....	3,169.19
.....	......	.....	.....	......	......	.....	5,160.29
.....	......	.....	.....	$ 11.25	......	.....	6,093.93
$420.15	......	.....	.....	......	......	.....	6,388.20
106.25	......	.....	.....	355.34[e]	......	1.91	9,694.54
.....	......	.....	.....	1,270.36[f]	......	41.84	9,644.91
8.00	......	.....	.....	362.31	......	8.79	5,870.41
8.00	......	.....	.....	......	......	.....	7,425.93
20.00	......	.....	.....	......	......	.....	7,890.01
16.50	......	.....	.....	......	......	.....	21,121.94
6.00	......	.....	.....	......	......	.....	21,081.68
7.00	$ 985.59	$ 62.80	.....	......	......	.....	25,334.31
12.80	483.00	130.65	.....	......	......	.....	32,964.01
13.00	2,172.00	135.87	.....	......	......	.....	34,233.95
12.40	178.50	100.20	($ 14.73)[d]	......	......	77.64	33,159.29
23.26	......	.....	(37.09)[d]	......	......	67.33	36,179.29
21.49	......	32.44	(62.49)[d]	300.00	$3,705.22	30.21	42,969.91
$674.85	$3,819.09	$461.96	($114.31)[d]	$2,299.26	$3,705.22	$228.08	$318,495.36
				June 30, 1952, Permanent Fund			7,291.06
				Cash Reserve			16,204.07
				Check total receipts			$341,990.49

APPENDIX I--MEMBERSHIP, DATES OF INCREASE IN LIMIT OF MEMBERSHIP, AND ORIGIN AND INCREASE OF ANNUAL DUES, AMERICAN GEOPHYSICAL UNION, 1921-1952

The accompanying diagram is a record of the membership and annual contributions from members, as authorized by the National Research Council, beginning in 1932. The remarkable growth in membership shown is the result of the successive Committees on Membership and their respective Chairmen. The Union is particularly indebted to H. Freeborn Johnston, for many years Chairman and now a member of the Committee; he has most unselfishly devoted his leisure spare time to the selection of prospective members. The Union is much indebted to him for its growth in number of members and thereby to the success in bringing Geophysics to the stature of a profession. In June, 1952, the total number of members was nearly 5000, including regular, associate, corresponding (foreign), life, and ex-officio members all over the world.



Membership, dates of increase in membership limit, and origin and increase of annual dues, American Geophysical Union, 1921-1952

APPENDIX J--LIST OF PUBLICATIONS OF THE AMERICAN GEOPHYSICAL UNION FROM 1920 TO 1953
(Corrected to January 15, 1954)

Volume No.	Year	Title	No. pages	Price postpaid
1	1920*	Transactions (Reprint and Circular Series, National Research Council No. 11)	57	$0.60
2	1921*	Transactions (Bull. National Research Council, No. 17)	108	1.50
3	1922*	Not published	..	...
4	1923*	Transactions (Bull. NRC, No. 41)	150	2.00
5	1924*	Not published	..	...
6	1925*	Transactions (Bull. NRC, No. 53)	80	1.00
7	1926*	Transactions (Bull. NRC, No. 56)	134	1.25
8	1927*	Transactions (Bull. NRC, No. 61)	297	3.00
9	1928*	Transactions (Bull. NRC, No. 68)	103	1.00
10-11	1929-30*	Transactions (all Sections)	314	1.50
12	1931*	Transactions (all Sections)	229	1.50
13	1932*	Transactions (all Sections)	401	2.00
14[a]	1933*	Transactions (all Sections)	521	2.50
15	1934*	Transactions Part I (all Sections except Hydrology)	258	1.25
	1934*	Transactions Part II (Hydrology)	376	1.50
16	1935	Transactions Part I (all Sections except Hydrology)	364	2.00
	1935*	Transactions Part II (Hydrology)	166	1.50
17	1936*	Transactions Part I (all Sections except Hydrology)	260	1.50
	1936*	Transactions Part II (Hydrology and Regional Meetings, Hydrology)	304	2.00
18	1937*	Transactions Part I (all Sections except Hydrology)	264	1.75
	1937*	Transactions Part II (Hydrology and Regional Meetings, Hydrology)	300	2.25
19	1938*	Transactions Part I (all Sections)	585	3.50
	1938*	Transactions Part II (Regional Meetings, Hydrology)	159	1.25
20	1939	Transactions Part I (Regional Meetings, Hydrology)	140	1.25
	1939	Transactions Part II (Symposium on floods)	94	1.00
	1939*	Transactions Part III (all Sections except Hydrology)	250	1.75
	1939	Transactions Part IV (Hydrology)	257	1.75
21	1940	Transactions Part I (Stanford University, Regional Meetings, Hydrology)	144	1.25
	1940*	Transactions Part II (Washington Annual Meetings, all Sections)	632	3.75
	1940	Transactions Part III (Richmond Symposium and Seattle Regional Meetings, Hydrology)	285	1.75
	1940	Transactions Part IV (Columbus symposia: Applications of mathematics in the earth-sciences and Hydrologic problems in the Ohio and Michigan basins	86	1.00
22	1941	Transactions Part I (Sacramento Regional Meeting, Hydrology)	216	1.50
	1941	Transactions Part II (Washington Annual Meetings, (all Sections except Hydrology)	368	2.50
	1941	Transactions Part III (Washington Annual Meeting, Hydrology)	452	3.00
23	1942*	Transactions Part I (Dallas and Pasadena Regional Meetings, Hydrology)	172	1.25
	1942*	Transactions Part II (Washington Annual Meetings, all Sections)	570	4.50
24	1943*	Transactions Part I (Washington Annual Meetings, all Sections except Hydrology)	332	3.50
	1943*	Transactions Part II (Washington Annual Meeting, Hydrology)	454	4.00
	1943	Transactions Part III (Corvallis Regional Meeting, Hydrology, and Western Snow Conference) and Addendum	105	1.00

[a] Although Transactions of 1933 as a whole are exhausted, the Papers and Reports of the following Sections are available: Meteorology, 40 pp., $0.40; Hydrology, 185 pp., $1.50.

*Out of print.

Volume No.	Year	Title	No. pages	Price postpaid
25	1944	Transactions Part I (Berkeley Regional Meeting, Hydrology, and Western Snow Conference)	187	$2.00
	1944	Transactions Part II (Washington Annual Meeting, General Assembly, Geodesy, Seismology, Minutes all Meetings)	203	2.00
	1944*	Transactions Part III (Washington Annual Meeting, Meteorology)	138	1.50
	1944*	Transactions Part IV (Washington Annual Meeting, Terrestrial Magnetism and Electricity, Oceanography, Volcanology, and Tectonophysics)	142	1.50
	1944	Transactions Part V (Washington Annual Meeting, Hydrology: Reports)	160	1.50
	1944	Transactions Part VI (Washington Annual Meeting, Hydrology: Papers)	236	2.00

Beginning of bimonthly		Feb.	Apr.	June	Aug.	Oct.	Dec.	No. of pages	Volume
26	1945	....	....	....	$1.50	$1.50	$1.50	482	$3.75
27	1946	$1.50	$1.50	$1.50	1.50	1.50	1.50	926	7.50
28	1947	1.50*	1.50*	1.50*	1.50	1.50	1.50	980	7.50**
29	1948	1.50	1.50[b]	1.50	1.50[c]	1.50	1.50	956	7.50
30	1949	1.50[b]	1.50	1.50*	1.50	1.50	1.50	950	7.50**
31	1950	2.00*	2.00	2.00	2.00	2.00[c]	2.00	968	9.00**
32	1951	2.00*	2.00*	2.00	2.00*	2.00	2.00	964	9.00**
33	1952	2.00	2.00	2.00	2.00*	2.00*[c]	2.00*	956	9.00**
34	1953	2.00*	2.00*	2.00*	2.00	2.00	2.00	986	9.00**
35	1954		The price of $9.00 has been set for subscriptions.						

Special publications	Year	Title	No. pages	Price postpaid
	1920-44	Index (combined author and subject), volumes 1-25	144	4.00
		Bibliography of Hydrology, United States of America:		
	(1937)*	Years 1935 and 1936	78	0.30
	(1938)*	Year 1937	68	0.30
	(1939)*	Year 1938	78	0.30
	(1940)	Year 1939	86	0.50
	(1941)	Year 1940	90	0.85
		Years 1941-1950 available through Government Printing Office, Washington, D. C., at a price of $1.75	408	...
		Lists of Members and Officers[d]		
	1948	July 10, 1948 (Part 2 of August 1948)	79	1.00
	1950	September 10, 1950 (Part 2 of October 1950)	116	1.50
	1952	September 10, 1952 (Part 2 of October 1952)	120	1.50
		Survey of Scientists Engaged in Geophysical Researches (for U. S. Research and Development Board), June 25, 1948, not available for distribution	158	...

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[b] Available only in complete or remaining partial sets.

[c] With these numbers, a Part 2 was issued, separately paginated, as a list of members and officers. These are not included in the volume or set, but may be purchased separately. They are listed directly above under the special publications.

[d] Earlier lists of members, published in 1939, 1940, 1942, 1943, and 1947 no longer available.

*Out of print.

**In these cases, the complete volume is not available. Orders including all remaining issues of a volume may be placed at a pro rata rate; for example, five of the six numbers for 1950 are still available, the price being 5/6 of $9.00 or $7.50.

In addition to the publications noted above, 47 special exhibits (chiefly maps) were prepared in 1939, these relating to the work of the Special Committees on the Geophysical and Geological Study of Ocean Basins and of Continents for the Seventh General Assembly of the International Union of Geodesy and Geophysics. Ozalid prints of these will be made on order. Information concerning them will be supplied on application [see Appendix K].

Orders, with checks payable to the American Geophysical Union, should be addressed to

American Geophysical Union
1530 P Street, Northwest
Washington 5, D.C., U.S.A.

APPENDIX K--INTERNATIONAL ASPECTS OF THE AMERICAN GEOPHYSICAL UNION

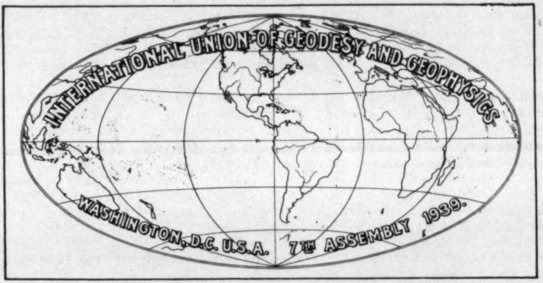
Some aspects of the functioning of the American Geophysical Union as the National Committee from the United States have already been discussed. Brief supplementary information is added here.

The Union has made free distribution of about 200 copies of its Transactions each year to members abroad of the International Union of Geodesy and Geophysics and to other interested geophysicists and geophysical organizations. During later years many prominent geophysicists of Central and South America, Australia, Europe, China, Africa, Great Britain, Pakistan, and India have taken advantage of the provision in the Statutes of the Union by which "the nationals of other countries . . . elected by the Executive Committee of the Union may become members although they may not vote or be officers of the Union or of its Sections, or delegates of the Union to International Assemblies or Meetings." At the present time (July 1952) a total number of foreign addresses to which the Transactions are regularly sent either because of individual paid membership or as free exchange in countries other than the United States is approximately 900.

The Union has been represented by delegates and guests, in increasing numbers, at each of the nine General Assemblies of the International Union of Geodesy and Geophysics. All of these Assemblies, except the Seventh in 1939, were held in European cities. The United States delegates and guests at the Brussels (Ninth Assembly) in 1951 numbered more than 100.

The Seventh Assembly was held in Washington through the efforts of the Union in cooperation with the Department of State and other groups. That Assembly was judged by our foreign colleagues to be one of the most successful from both points of view of attendance and scientific discussion.

To accomplish this undertaking the American Geophysical Union found, in addition to its own funds, some $18,327 to cover expenses. In addition to gratuitous services of many members, over one-sixth of the funds expended was provided through donations by members and friends of the Union. The remainder was obtained through generous special grants from (1) the United States Government, (2) the National Research Council, (3) the Geological Society of America, and (4) the Carnegie Corporation, in almost equal shares of $2,700 after refund of $300 to each of the last three named.


INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS
WASHINGTON, D.C. U.S.A. 7TH ASSEMBLY 1939.

Special emblem, prepared by the U. S. Coast and Geodetic Survey, for General Assembly in Washington in 1949

It was fortunate indeed that the Seventh Assembly, coming at the time almost simultaneously with the outbreak of hostilities, was held in the United States. Despite the interference since then, as a result of World War II, with the operation of the International Union of Geodesy and Geophysics, it has been possible, with our colleagues in the various member countries of the United Nations, to maintain a considerable part of the functioning of the international body. Thus its continuance was ensured and certainty of resumption of its important program assured promptly at the end of the War. This was done largely through the efforts of the officers of the International Union in Great Britain and those in the United States.

The accompanying statement shows the receipts and disbursements at the close of business December 18, 1939, for the Seventh General Assembly of the International Union of Geodesy and Geophysics. The disbursements in this statement included payments made for expenses of three International Associations at the Washington Assembly upon due authority for subsequent reimbursement. Bills receivable (December 18, 1939) on account of these for reimbursement to the Finance Committee of the Assembly totalled $332.49.

Summary of report of Treasurer of Finance Committee for Washington Assembly as of December 18, 1939

Receipts		
United States Government	$2,660.68	
National Research Council	3,000.00	
Geological Society of America	3,000.00	
Carnegie Corporation of New York	3,000.00	
American Geophysical Union members ($2,664.20) and friends ($1,491.50)	4,155.70	
Registration fees	2,047.50	
Miscellaneous refunds in 1939	462.73	
Total Receipts		$18,326.61
Disbursements by Washington Assembly Committees		
Organizing	$1,158.09	
Finance	100.00	
Local secretaries	53.68	
Coordinated interests	40.20	
Meeting places, hotels, etc.	38.20	
Office	7,239.25	
Publicity	487.45	
Travel	855.37	
Exhibits	394.74	
Entertainment	2,863.62	
Ladies entertainment	432.90	
Special exhibit	913.05	
Special contingency	493.16	
Total disbursements		15,069.71
Balance		$ 3,256.90

Many American delegates and guests at the Assembly, including a large number of the members of the American Geophysical Union, asked that they be supplied, if possible, with copies of the printed transactions of one or more of the Associations and of the International Union. These requests totalled over 1500 volumes. An appropriate liability was assumed by the Union on this account.

The allotment from the United States Government was $4,500.00, of which (largely because of the non-attendance of about 50 pct of those who had expected to attend from abroad) only $2,660.68 was expended, through the Department of State for services, printing, and entertainment. The balance in the Government allotment was $1,839.32 and was reverted. The cost of 1800 volumes of transactions and mailing was estimated at $1,756.90, which left an unexpended balance in the funds of 1,500.00 plus bills payable of $332.49. The net balance of receipts was prorated, by action of the Union's Executive Committee, on the basis of original contributions of $3,000.00 each (1) from the National Research Council, (2) from the Geological Society of America, and (3) from the Carnegie Corporation of New York, with revertments to each of $300.00.

Special publications and exhibits were prepared in connection with the Seventh General Assembly as shown on the accompanying lists.

Special publications by the American Geophysical Union in connection with the General Assembly of the International Union of Geodesy and Geophysics at Washington in 1939

List of Delegates and Guests, IUGG, Seventh General Assembly, Washington, Sept. 4-15, 1939; 96 pp., with 488 reproductions of photographs of over 80 pct of delegates and guests, Washington, 1939.

Day-by-Day Program of Activities of the Washington Assembly of the International Union of Geodesy and Geophysics and its seven Associations; a leaflet 8 1/2 by 21 inches, showing activities for each day of meetings for the Union and for each of the Associations, folded to 8 1/2 by 5 1/4 inches, Washington, 1939.

Que Faut-il Voir à Washington? Guide Concis de la Capitale des Etats Unis, an authorized translation of the English brochure (third and revised edition) by Mary O. Sumner; for distribution to the delegates and guests attending the Washington Assembly; 31 pp. with numerous half tones of buildings and places of interest, Washington, 1939.

Special exhibit maps of the American Geophysical Union assembled for Seventh General Assembly, International Union of Geodesy and Geophysics in 1939

No.	Description	Number of sheets	Size of map (no margins)		Price[a] post-paid
			N-S	E-W	
			inch	inch	
1	Reconnaissance structure-contour map of surface of basement-complex in U. S.	4	45 1/4	72 1/2	$6.00
2	Iso-anomaly map of U. S., 60-km depth of compensation (1936)	2	48	75 3/4	6.00
3	Iso-anomaly map of eastern U. S., 113.7-km depth of compensation (1938)	1	47	35 1/2	3.00
4	Normal warp iso-anomaly map of U. S. (1937)	1	46	40	3.00
5	Gravitational and structural trends in eastern U. S.	1	40	27 1/2	3.00
6	Gravity profiles across eastern U. S. (1938)	1	16	16 3/4	0.40
7	Geologic map of the U.S. (U.S. G.S. Pub.)	4	50	75	. . .[b]
8	United States seismic-epicenter map	1	42	78 1/2	4.50
9	"Geothermal-gradient" map of the U. S.	4	45	72 3/4	5.00
10	Map showing variation of carbon ratios of Cretaceous and Tertiary coals in U. S.	1	29 1/4	37 1/4	1.50
11	Map showing variation of carbon ratios of Carboniferous coals in the U. S.	1	24 1/2	34	1.50
12	Geologic map of Beartooth-Bighorn-Black Hills Region	1	28 1/2	69 1/2	4.50
13	Iso-anomaly map of Beartooth-Bighorn Region	1	38 1/4	43 1/2	3.00
14	Normal warp iso-anomaly of Beartooth-Bighorn-Black Hills Region	1	28	52	2.00
15	Geologic and gravitational profiles across Beartooth-Bighorn-Black Hills Region	1	16 3/4	41 1/2	1.25
16	Geologic map of New Jersey (N. J. State G.S. Pub.)	1	46 1/2	25	. . .[c]
17	Seismic and geologic cross-section for Barnegat Bay traverse, New Jersey	1	26	48 1/2	2.00
18	Cape May, New Jersey, seismic and geologic profiles	1	32	70	6.00
19	New Jersey velocity-gravity sections on Cape May and Barnegat Bay profiles	1	40 1/2	36 3/4	3.00
20	Structural analysis of geologic-seismic data for the Plainsboro area, New Jersey	1	22 1/2	41 3/4	1.50
21	Map showing extension of the Palisades Diabase (N. J.) based on magnetic and geologic data	1	18 1/4	40 3/4	1.25
22	Key map showing location of geophysical sections across Atlantic Coastal Plain	1	27 1/4	19 1/4	1.25
23	Geologic map of Virginia Region	1	19 1/2	24 1/4	0.75
24	Basement-surface contour map, Virginia	1	18 1/4	25 1/4	0.75
25	Gravity iso-anomaly map of Virginia Region	1	18 3/4	25	0.75
26	Seismic, gravitational, and geologic profiles for Cape Henry, Virginia, and Barnegat Bay, N. J., sections	1	18	19 1/2	0.75
27	Geologic, gravitational, and "computed-density" sections across Virginia Region	1	16 3/4	23 3/4	0.75
28	Bathymetric map of Bermuda area	1	17	19 1/2	0.75
29	Bathymetric cross-sections, Bermuda area	1	13 3/4	23 1/2	0.75
30	Cross-section of Bermuda Seismograph Station	1	18 1/4	26 1/2	0.75
31	Chart showing correlations between weather conditions, rate of tilt, and microseismic activity at Bermuda	1	20 3/4	54	2.25
32	Map showing position of Bermuda relative to Mid-Atlantic Seismic Zone	1	16 1/4	11 1/4	0.40
33	Isogonic map of Bermuda (1935)	1	9 5/8	18 1/8	0.40
34	Vertical-intensity magnetic map of St. George's, Bermuda	1	17	20 3/4	0.40
35	Graphic illustration of shallow-water marine seismic technique	1	24	40 1/8	1.50
36	Graphic indication of moderate-depth marine seismic technique	1	27 3/4	40	2.00

(Continued)

Special exhibit maps of the American Geophysical Union assembled for Seventh General Assembly, International Union of Geodesy and Geophysics in 1939 (concluded)

No.	Description	Number of sheets	Size of map (no margins)		Price[a] post-paid
			N-S	E-W	
			inch	inch	
37	Graphic indication of deep-sea seismic technique	1	29 1/4	40 1/4	$2.00
38	Chart indicating comparative depths at which marine seismic work is being done	1	40 1/2	17 5/8	1.25
39	Diagram showing recording oscillograph as used in deep-sea seismic measurements	1	40 1/4	26 3/4	1.50
40	Iso-anomaly map of Gulf-West Indian Region	1	30 1/2	51 1/2	3.00
41	Map showing geophysical methods used in discovery of Texas and Louisiana Gulf Coast Oil Fields	1	35	32	3.75
42	Map showing geophysical method used in discovery of oil fields in Illinois Basin	1	32 1/2	25 1/2	2.25
43	Basement-surface sections across United States	1	19 1/2	58	2.00
44	Gravitational and basement-section across U. S.	1	35	32	3.00
45	Gravity-station map of U. S. (1939)	2	49 1/2	75	5.25
46	"Vertical-intensity" magnetic sections across Palisade Diabase (Sill)	1	45	39	3.00
47	Graph comparing oil production and estimated reserves of oil and new fields, Illinois Basin, July, 1939	1	20	11 1/4	0.40
48	Graph comparing oil production and estimated reserves, Gulf Coast Region	1	18 1/2	42 3/4	1.25
49	"Vertical-intensity" magnetic section along Barnegat Bay traverse	1	32	47 3/4	1.25
50	Model showing approximate configuration of surface of basement complex in U. S.	Approx. 50 by 75 inches			. . .[d]

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[a] Prices are for ozalid prints made on order - minimum order $4.00; prices subject to change.

[b] The regular U. S. Geological Survey 1/2,500,000 geologic map of the United States was used as special exhibit 7 for comparison with exhibits 1-11.

[c] The New Jersey Geological Survey's regular 1/250,000 State map was used as special exhibit 16 for comparison with exhibits 17-21, etc.

[d] No longer available.

American Geophysical Union Excursion to Luray, Virginia, Sunday, September 10, 1939, description of points of scenic, historic, and geologic interest between Washington, D. C., and Luray, Virginia, by Marcellus H. Stow (of Washington and Lee University) and Luray Caverns in Virginia, by William H. McGill (Assistant State Geologist of Virginia), 20 pp. with map of the Excursion prepared by the U. S. Geological Survey (scale, one inch = four miles).

Road Map of Washington and Vicinity, 1938, prepared by the Geological Survey of the U. S. Department of Interior, 16 1/2 by 20 inches, scale four miles to one inch (folded for pocket use), 4 1/4 by 5 inches, Washington, 1938.

International Association of Geodesy, Seventh General Assembly, Washington, September, 1939; 64 pp., Washington, 1942.

Washington Standard Guide (revision of 1939), 200 illustrations and 163 pp., and insert of Ready Reference Map and Index of Washington (scale 3 3/4 inches = 1 mile); published by B. F. Reynolds Co., Washington, 1939.

Publications, specially prepared by others, presented to each delegate and guest

Descriptive Pamphlet of Mount Vernon, Virginia, issued by the Mount Vernon Ladies' Association; folded into 8 pp., four by nine inches, May, 1939.

Guide Map of Capital Transit Street Car and Bus Lines, by the Capital Transit Company, 27 by 50 inches folded to 4 by 8 1/4 inches, with half-tone and descriptions of chief places of interest, key, and index of routes, streets, etc., Washington, 1939.

Pamphlet of the George Washington University at Washington, with historic and descriptive accounts of its formation and sketch of campus and buildings; 16 pp., 9 by 12 inches.

Transactions, American Geophysical Union Volume 35, Number 1 February 1954

SYMPOSIUM

THE INTERIOR OF THE EARTH

Presented at the Thirty-Fourth Annual Meeting
American Geophysical Union
May 4-5, 1953

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Transactions, American Geophysical Union Volume 35, Number 1 February 1954

SYMPOSIUM ON THE INTERIOR OF THE EARTH[a]

OPENING REMARKS

Walter H. Bucher

The work of the geologist and geophysicist has much in common with that of the physician. The work of both groups of men deals with a living body of which only the surface and such processes as are active on it are visible. Both want to know what goes on within, but must be content to base their diagnoses on indirect evidence. Both deal with the baffling complexity of unabstracted reality and look with envy on the basic sciences which achieve precision by lopping off all but the one process or property they are exploring. Both must go to the basic sciences for the understanding of what they observe, and both need men who bridge the gap between the concrete phenomena and the abstract processes - geophysicists and geochemists on the one hand and biophysicists and biochemists on the other.

But there are two fatal differences that separate him who studies the Earth from his confrère in medicine: The latter can check his generalizations on whole armies of individuals. The student of the Earth has but one individual to study. And that individual is of such a size that before it man is like a microbe on the dome of Saint Peter.

It is the glory of us microbes that our minds can visualize what our eyes cannot see. And so we crawl over our patient, observing, probing, diagnosing. Some of us, the geologists, are the dermatologists, observing swellings and pock marks, fluids that ooze out and layers that slough off on the surface. Others are concerned with the more vital inwards of the Earth. Where formerly the baffled doctors made shrewd guesses, now they have the equivalents of the stethoscope, the cardiograph, the X-ray - they are the specialists of the interior of the Earth.

Three years ago your President, a geologist, gave a report on the large problems of the Earth's dermatology. When you reelected him, he had to plan for another presidential address. If this were a Union of terrestrial dermatologists, he could have served up more than one acceptable dish of specialized knowledge. But we are proud of our function as a Union of men who get together at intervals to see the ultimate object of their studies in broad perspective. So your President decided upon a departure from custom, not to dodge his duty, but to fulfil it in a larger measure. Having himself spoken on the Earth's skin, he invited now a number of specialists to round out the picture of the Earth in a Symposium on the Interior of the Earth.

We start with the heart of the matter, the core of the Earth. We have with us some of our own great cardiologists of the Earth, who will then speak. For the opening address, your President has invited a leader among the younger generation of geophysicists of England, in conformity with the Union's basic purpose to help creative workers to overcome the handicaps of geographic separation while they are in the midst of their most fruitful years.

It gives me great pleasure to present to you the Assistant Director of the Geophysical Laboratory of Cambridge University, Professor Stanley Keith Runcorn.

Department of Geology,
Columbia University,
New York 27, New York

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[a] This Symposium, consisting of the papers and discussions here published, were presented on May 4 and 5, 1953, in connection with the Thirty-Fourth Annual Meeting. The papers and discussions comprising it are open for formal discussion until July 1, 1954.

THE EARTH'S CORE

S. K. Runcorn

Abstract--The modern view of the origin of the geomagnetic field associates it with motions in the liquid core of the Earth. This new approach, suggested by W. Elsasser, has led to a revival of interest in the main geomagnetic field and phenomena connected with it. The hypothesis of motions in the Earth's core not only accounts for the remarkably rapid changes in the geomagnetic field but also for the irregular fluctuations in the rate of rotation of the Earth.

E. C. Bullard has given convincing arguments for the belief that these motions in the Earth's core arise from thermal convection. It may easily be demonstrated that the motions are to a high degree dominated by the Coriolis forces arising from the Earth's rotation. Consequently model experiments on thermal convection under the influence of Coriolis forces are of great importance in understanding the physics of the Earth's core. Such experiments, done by R. Hide of the Department of Geodesy and Geophysics of Cambridge University, give rise to an interesting explanation of the westerly drift of the geomagnetic field, discovered by E. H. Vestine, and give patterns of motion involving jet streams, which are incidentally of remarkable similarity to the motions in the upper atmosphere.

The essentially two-dimensional motions which result from the dominance of the Coriolis forces are thought to supply a fundamental reason for the axial character of the geomagnetic field. Though much is known about the physical processes in the core relating to the geomagnetic field, the mechanisms by which these motions set up electromotive forces are still obscure, though two lines of approach look promising. The first is that the motions maintain the field by a dynamo action and the second is that they set up temperature distributions which give rise to thermoelectric currents.

Introduction--The existence within the Earth of a liquid core of radius approximately 3500 km was firmly established by seismological studies, though its fluid character may be inferred from the analysis of the lunar bodily tide of the Earth. The density of the core as a function of radial distance is deduced from the variation of the seismic velocities with depth together with the knowledge of the mean density of the Earth and its moment of inertia, the latter being determined from the precession of the equinoxes. The chemical constitution of the Earth's core has recently been discussed somewhat controversially. It was generally believed to be molten iron-nickel but the view has been put forward recently, mainly by RAMSEY [1948], that it consists of a high-pressure modification of olivine. It seemed to some of us that the arguments advanced against an iron-nickel core were ineffective and this point of view has been well summarized by BIRCH [1952]. However, from our standpoint it is sufficient to regard the core as having metallic characteristics, notably appreciable electrical conductivity. The existence within the core of a solid central body with a radius of about 1300 km seems required by seismological data and will be assumed in this discussion.

The geomagnetic secular variation and the irregular changes in the length of the day--Perhaps the most important recent development in the study of the Earth's core has come through the recognition that the geomagnetic field with its secular variation has its origin in physical processes in the liquid core. ELSASSER [1939] was the first to recognize this; he pointed out that it was natural to associate the geomagnetic secular variation with fluid motions in the deep interior of the Earth because physical processes in the solid mantle of the Earth would be associated with a much longer time scale. In this paper Elsasser made rough estimates of the velocity of the relative motions in the core by supposing the lifetime of a center of the secular variation to be of the order of the period of rotation of a large eddy in the core. He found velocities of the order of 1 mm/sec. Elsasser went on to suggest that the temperature and pressure differences in the fluid, associated with the motions, would produce thermoelectromotive forces directed along lines of latitude, but he noted that the effect was too small and in later papers he has reverted to the view originally suggested by LARMOR [1919] that motions in a conducting fluid may amplify (by electromagnetic induction) any small field which may be originally present and maintain it at a strength dependent on the mechanical energy available. This "dynamo" theory of the geomagnetic field has been extensively discussed by ELSASSER [1946ab, 1947] and by BULLARD [1949ab], but it has still to be proved that amplification of the field external to the conducting sphere can be effected; there is no doubt that the average field intensity within the sphere can be increased by the fluid motions. However, it is not immediately necessary to discuss the precise mechanism by which the core motions generate a field in order to throw light on some of the interesting processes in the Earth's core.

The publication by VESTINE and his Collaborators [1947] of geomagnetic maps and tables, summarizing the results of the magnetic surveys undertaken and observatory data available from the beginning of this century, and spherical harmonic analyses of the field and its secular variation based upon them, has revealed in a striking way evidence in favor of the origin of the geomagnetic field in a fluid core. It had long been realized that the secular variation has a regional rather than a planetary character; it cannot be represented, as Schmidt thought, as a central inclined dipole precessing about the geographical axis. The distribution of the secular variation appears to indicate a number of active areas, in which the field is changing rapidly, and which grow and decay independently of one another. Thus Vestine's maps show a considerable change in the pattern of the secular variation between the epochs 1932.5 and 1942.5 It has been shown by LOWES and RUNCORN [1951] that the observed distribution of the secular variation may be well explained by a small number of varying horizontal current loops at the surface of the core, the magnetic fields of which at the Earth's surface are closely approximated by vertical dipoles 1000 km beneath the center of each loop. This simple representation of the current systems producing the secular-variation field demonstrates that the distribution of the latter is consistent with an origin as deep as the core. It can also be concluded that the pattern of motion producing the electric current may likewise be visualized simply as a convection pattern with a small number of lobes or eddies.

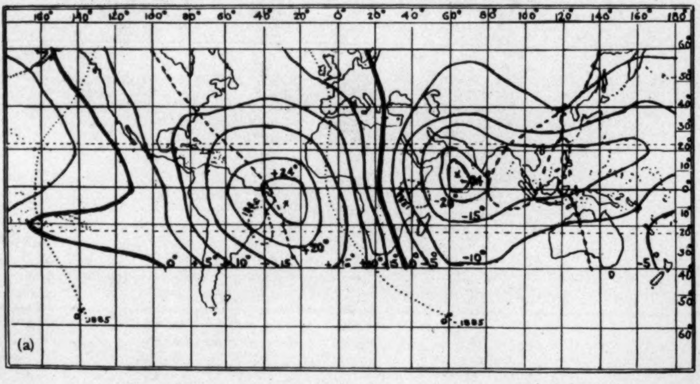
(a)
160° 140° 120° 100° 80° 60° 40° 20° 0° 20° 40° 60° 80° 100° 120° 140° 160° 180°
60 50 40 30 20 10 0 10 20 30 40 50 60
+24°
+20°
-20
-15°
-10°
0° +5° +10° +15
-5
0
0°-1885
(b)
+27
+25°
+20°
-25°
-20°
-15
-10
0° +5° +10° +15 +20° +15° +10 +5 0° -5° -5°

Fig. 1--Isapoclinics after BAUER [1895, pp. 316-317], (a) for 1780, (b) for 1885

An even more remarkable characteristic of the secular variation is that the local maxima of change, that is, the isoporic foci, show a marked drift to the west. This was described by FLEMING [1948]. It can be said that all the non-axial features of the geomagnetic field show this steady drift to the west at a rate of the order of a few tenths of a degree of longitude per year. This is by no means a recent discovery for BAUER [1895], among others, had noticed it and the two little-known maps reproduced in Figure 1 from this paper vividly demonstrate the westward drift. In these maps for 1780 and 1885 Bauer exhibits the non-dipole field by subtracting from the observed angles of dip the values corresponding to an axial central dipole field. The lines on his maps, isanoporics as he called them, are lines of equal difference. The significance of the drift was only understood when it was realized that a simple model of the Earth in which the core was supposed to be electrically conducting and the mantle insulating would imply that the core was rotating relative to the mantle, carrying the magnetic field with it. The free decay time of a current system depends on the square of its linear dimensions and is always very long on the cosmic scale: thus magnetic lines of force tend to move with the conductor which they cut.

In 1951 A. F. Moore, then at the Department of Geodesy and Geophysics, Cambridge University, drew my attention to the possibility of some correlation between the irregular changes in the length of the day and the sudden changes in rate of the geomagnetic secular variation. The larger changes in both tend to occur every few decades - a time scale very different from that of other geophysical phenomena of the solid Earth. The demonstration that the observed longitude of the Moon differs significantly from those calculated from the gravitational theory of the Moon forms a most fascinating chapter of astronomical literature. That these fluctuations in the longitude of the Moon might result from changes in the rate of rotation of the Earth was early recognized by NEWCOMB [1912]. DE SITTER [1927ab] represented the data by instantaneous changes in velocity occurring irregularly every few decades. The demonstration by SPENCER JONES [1939] that the same fluctuations appeared in the motions of the Sun and the inner planets, when due allowance was made for the difference in their mean motions, finally made it clear that what were being observed were irregular fluctuations in the angular velocity of the Earth. It was early recognized that changes on the Earth's surface or in the atmosphere were quite insufficient to account for the magnitude of these changes in the Earth's rotation, a conclusion which has recently been confirmed by MUNK and REVELLE [1952]. Thus Moore's suggestion led me naturally to associate these changes with the motions in the Earth's core which we have already seen lie at the root of the explanation of the secular variation. Suppose as a first approximation to a discussion of the transport of angular momentum between the core and the mantle that the core revolves as a rigid body during the changes. Then the conservation of the angular momentum of the whole Earth gives the following relationship between a change (increase) in the length of the day (δT seconds) and the corresponding change (increase) in the rate of the westward drift of the core with respect to the mantle ($\delta\Omega$ degrees of longitude per year)

$$\delta T = -0.067\,\delta\Omega \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

the moments of inertia of the core and the mantle being taken as 8.48×10^{43} and 8.10×10^{44} gm cm^2 respectively. Eq. (1) indicates that a 20 pct change in the rate of the westward drift would be sufficient to change the length of the day by the largest amount which has yet been observed, that is, the increase of 0.003 sec observed about 1897.

The explanation of the irregular change in the length of the day has also been undertaken in terms of motions in the core independently of the present author by VESTINE [1952] and by MUNK and REVELLE [1952]. They use BULLARD's [1949a] model of the Earth's core in which it is supposed that the convective motions within the core transport angular momentum from the inner half of the core (by volume) to the outer half; thus the outer part of the core is continually being retarded relative to the inner.

It is easily seen that the transfer of angular momentum between the core and the mantle is effected by electromagnetic forces. Transfer by the detachment of a piece of the solid mantle, say, would seem to require changes in the length of the day in one direction only but it is characteristic of the irregular changes that they may have either sign. The viscous torques between the mantle and core are negligible. We now need to introduce a refinement into the Earth model which we have so far found adequate. In order that electromagnetic torques can operate on the mantle, its lower part has to be appreciably electrically conducting. The author in another paper to be published in these Transactions, and H. Hughes, in a paper in preparation, discuss the problem of what predictions can be made concerning the conductivity of the mantle on the basis of solid-state theory, assuming the mantle to consist of a silicate such as olivine or possibly an oxide, both of which are insulators under laboratory conditions. However, it is clear that at the elevated temperatures obtaining near the bottom of the mantle sufficient valence electrons are thermally excited into the conduction band of the crystal to produce appreciable electrical conductivity. The well-known discussion by LAHIRI and PRICE [1939] of the electrical conductivity of the upper thousand kilometers of the mantle, as deduced from studies of the transient variations of the geomagnetic field, apparently shows the onset of this effect. The hypothesis that electric current is flowing in the lower part of the mantle is necessary to provide the coupling to change the angular velocity of the core and mantle; a mathematical study of this electromagnetic problem will be published elsewhere. Equal and opposite torques must be applied to the core and the mantle. Now the graph of the fluctuations in the Moon's longitude against time shows comparatively long periods of constant slope, representing periods of constant angular velocity, separated by rather sudden changes of slope and angular velocity. There is some difficulty in determining the length of time taken for the changes to establish themselves: DE SITTER [1927ab] termed them "sudden changes," as indeed they are on the scale of most geophysical phenomena connected with the solid Earth. However, BROUWER [1952] indicates that de Sitter's view is not justified, the changes taking a few years to establish themselves, though we may expect the more exact methods of observation of the Moon now being used to furnish us in future with better data on this important point. The transient-current systems associated with such an impulsive torque on the mantle and core can hardly penetrate deeply into the core or extend far up into the mantle. This is an effect of electromagnetic induction similar to the "skin effect" of alternating-current theory. The depth of penetration of a magnetic field of period T into a conductor of electrical conductivity K emu equals $(1/2\pi)\sqrt{T/K}$. This formula gives exactly the distance in which the field falls off to 1/e of its value at the surface for the case of a semi-infinite solid with the field uniform and parallel to the interface and is of the right order of magnitude for other arrangements. We shall suppose that the impulsive torque is spread over four years: it will have a strong Fourier component of a period of eight years; the skin depth for the core is then 25 km, taking $K = 1000\ \text{ohm}^{-1}\ \text{cm}^{-1}$ and for the mantle and for the mantle is 250 km, taking K′ for the lower mantle equal to $10\ \text{ohm}^{-1}\ \text{cm}^{-1}$. Thus during a sudden change in the length of the day, an outer spherical shell of the core must experience a sudden torque. Due to the high conductivity of the core and the comparatively large magnetic fields inside it, the change of motion of the outer shell is transmitted to the whole core in a very short time. This time can be estimated easily from the velocity of a transverse mechanical disturbance in a conducting fluid in a magnetic field, which is termed a magnetohydrodynamic wave. ALFVÉN [1950] gives as the velocity V of a unidimensional transverse wave of this type in a fluid of density ρ and permeability μ and in a field H_o

$$V = H_o\sqrt{\mu/4\pi\rho}$$

Thus for the disturbance to transmit itself throughout the core in a time less than the duration of the change, that is, four years, V must be greater than about five cm/sec, that is, H_o must be greater than about 24 gauss, which is very likely so. The velocity V with which the disturbance is transmitted is independent of T but the distance Z_o in which the amplitude of the wave is reduced to 1/e of its initial value is given by $Z_o = \mu^{5/2} K H_o^3 T^2/4\pi^{5/2}\rho^{3/2}$ and thus rapidly decreases as the period decreases. However, for T = 4 years, Z_o is very much greater than the radius of the core. It seems likely then that a sudden torque administered to an outer part of the core will result in a transfer of angular momentum to the core as a whole. Thus the use of Bullard's model of the core, as in Vestine's and Munk and Revelle's discussion of the problem, seems very dubious.

VESTINE [1952] has established that there is a significant change in the rate of the westward drift over the last 50 years, which is of the order of magnitude demanded by the above discussions. Unfortunately there is a wide divergence between the westerly drift as derived from the eccentric dipole, which Vestine uses and the value of the drift obtained from the movement of the isoporic foci and of the foci of the non-dipole field [BULLARD and Others, 1950]. It is therefore somewhat difficult to use Vestine's value as a test as to whether the core moves as a whole during the changes in the length of the day.

The magnetic fields and electric currents which can exist in the lower part of the Earth's mantle assuming that it is uniformly conducting out to a certain radius, say about 4500 km, are of two types, the electric mode and the magnetic mode. The electric mode has a magnetic field $\vec{H}_E$ with no radial component, which is produced by a current system $\vec{I}_E$ with radial components, which must originate in the core or on the core-mantle interface, as there can hardly be sources of electromotive force in the mantle. The magnetic mode has a magnetic field $\vec{H}_M$ the lowest harmonic of which is the simple dipole type of field; a current system $\vec{I}_M$ is induced if the field $\vec{H}_M$ is changing. The torques which alter the rotation of the mantle must result from the interaction of these fields and currents. It can be shown (the proof will be discussed in detail elsewhere) that only the interactions between $\vec{I}_M$ and $\vec{H}_M$, between $\vec{I}_E$ and $\vec{H}_M$, and between $\vec{H}_E$ and $\vec{I}_M$ give net torques and only for certain harmonics. The magnitude of the $\vec{I_M}$ - $\vec{H_M}$ interactions seems inadequate to account for the torques required. Because of this, one must suppose that considerable fields of the electric-mode type are present in the lower mantle; these would be the result of current flow crossing the core-mantle interface. As we have seen, these currents cannot arise deep in the core if they are varying rapidly. This leads us to postulate the presence of electromotive forces on the core-mantle boundary, which leads to a suggested origin of the main field.

Model experiments on the fluid motions in the Earth's core--The character of the internal motions in the core is not easy to determine. Strong reasons have been given for the belief that they result from thermal convection [BULLARD, 1949a] and we shall take as a convenient model the one due to ELSASSER [1950] in which the central body is supposed to be the heat source because of a slight concentration of the heavy oxides of the radioactive elements towards the center of the Earth.

A remarkable feature of the hydrodynamics of the core, which has not been sufficiently emphasized, is the tremendous dominance of the Coriolis forces over the other terms in the hydrodynamical equations. The equation of motion for a viscous, electrically conducting liquid of viscosity ν, density ρ, and volume coefficient of expansion β, in which electric currents of density $\vec{i}$, are flowing, is

$$d\vec{v}/dt + (\vec{v}\cdot\nabla)\vec{v} + 2\vec{w} \wedge \vec{v} - \nu\nabla^2\vec{v}/\rho + \mu\vec{i} \wedge \vec{H}/\rho = -\nabla p/\rho + \vec{g}(1+T\beta) \quad \ldots\ldots\ldots (2)$$

where $\vec{v}$ is the velocity vector, $\vec{H}$ the magnetic field vector, $\vec{w}$ the angular velocity vector of the Earth, p the fluid pressure, T the temperature field driving the convection, and $\vec{g}$ the value of gravity. Table I shows the dimensions and the orders of magnitude of the separate terms on the left-hand side of the equation. A length ℓ is taken typical of the size of the core motions responsible for the secular change, that is, about 1000 km. It is thus clear that it should be possible in the first instance to neglect all the terms on the left-hand side of the equation except the Coriolis force. It would appear that the most likely form that the core motions would take under these circumstances consists of a number of cylindrical vortices with their axes parallel to the geographical axis of the Earth, for if the vortices were inclined to the geographical axis they would not be able to resist the immense gyroscopic forces acting upon them. PROUDMAN [1916] showed that, in a rotating fluid of uniform density, slow steady motions are confined to planes perpendicular to the axis of rotation. It may be shown that there is a strong tendency in this case for the motions also to be two-dimensional. Omitting small terms, (2) becomes

Table 1--Dimensions and orders of magnitude of various terms in Eq. (2)

Term	dv/dt	$(v\cdot\nabla)\vec{v}$	$2\vec{w} \wedge \vec{v}$	$\nu\nabla^2\vec{v}/\rho$	$\mu\vec{i} \wedge \vec{H}/\rho$
Dimensional approximation	v/t	v^2/ℓ	$2\,w\,v$	$\nu v/\rho\ell^2$	$\mu i\ H/\rho$
Order of magnitude	310^{-12}	10^{-10}	2×10^{-5}	10^{-12} ($\nu = 10^6$)	2×10^{-9} (H = 3 gauss)

$$2\vec{w} \wedge \vec{v} = -\nabla p/\rho + \alpha(1+T\beta)\vec{r} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where $\vec{g} = \alpha\vec{r}$. The density is taken as a constant except in the buoyancy term.

Taking the curl of (3) we obtain $2(\vec{w}\cdot\nabla)\vec{v} = \alpha\beta\vec{r} \wedge \nabla T$ as $\nabla\cdot v = 0$.

Thus $d\vec{v}/dz = 0$, where z is distance along the geographical axis, and $v_z = 0$ for the temperature field will tend to be a radial one.

As a first approximation we can therefore expect the motion in the core to be largely two-dimensional. This seems to supply a fundamental reason for the outstanding feature of the main geomagnetic field, namely, its predominantly axial character. Though at any one time this symmetry about the axis of the Earth's rotation is somewhat obscured - at present the axis of the best central dipole makes an angle of about 11° to the geographical axis - there seems to be good evidence (to which reference will be made later) that, when averaged over a few hundreds or thousands of years, the non-axial components disappear.

The study of convection is linked to the name of BÉNARD [1901] who was the first to show experimentally that a layer of liquid with a vertical temperature gradient forms a network of cells, each of which in plan view is a hexagon. Each cell possesses the same flow pattern - the fluid usually rising in the center and falling at the sides - and its linear dimension is proportional to the depth of the fluid layer. The famous theoretical investigation of RAYLEIGH [1916] showed that a minimum temperature gradient was required to cause convection to begin if the fluid had a finite viscosity. Since this time the mathematical problem has been elaborated but from a physical point of view the formulation of the convection problem has been defective. The dependent variables in the problem are both the temperature and velocity distributions and they appear in the equations both of motion and of heat transfer. In order that the differential equation of the problem shall be linear, it is necessary to neglect terms containing the products of the two dependent variables. Thus the velocity distribution so derived from the solution of the equation is one which refers only to the case when convection is just possible and the heat carried by the convection, which is proportional to the product of the velocity and the temperature difference between the up-going and down-going streams, is vanishingly small. We shall see that this assumption is far from realistic in examples of convection of interest to the geophysicist. Further, nothing was known of the effect of the Coriolis force on the onset of convection or on the cellular pattern.

It was therefore decided to undertake a new experimental study of convection in circumstances more nearly representative of conditions in the core. In view of the suggested two-dimensional character of the motions in the core, it was thought reasonable to begin with a cylindrical model.

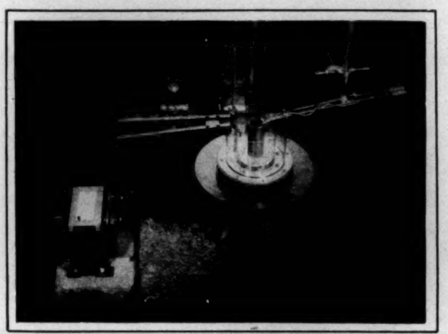

Fig. 2--View of the apparatus

Figure 2 shows the apparatus used. It consists of three concentric cylinders mounted on a platform which can be rotated about the vertical axis of the cylinders. The inner cylinder and outer annulus contain hot and cold water so that the fluid in the inner annulus, usually water, has a radial temperature gradient impressed on it. The fluid convects under the influence of gravity and the radial centrifugal force, the former being usually dominant, though a similar convection pattern is produced in each case. The apparatus is illuminated from the side and the motions at the top surface are shown up, as in the pictures in this paper, by the light scattered by aluminum powder on the surface of the water. HIDE [1953] has published a brief account of the experiment and is preparing a detailed account. It is simple to arrange for the Coriolis force to be dominant in these motions though not to the same extent as in the Earth's core. The viscous force remains relatively unimportant but by increasing the heat flow through the fluid, and therefore the velocity of the fluid, it is possible to make the inertia force $(\vec{v}\cdot\nabla)v$ more important than the Coriolis force and the resulting transition in the pattern of the motions is of considerable interest.

The relative importance of the Coriolis force is conveniently given by the non-dimensional Rossby number X, the ratio of the inertia force to the Coriolis force. For X greater than a critical value X_0 the motion takes the form of a three-dimensional motion; there are strong vertical motions in the fluid at the outer and inner cylindrical boundaries and the motion at the top surface takes the form of a tight spiral, as shown in Figure 3. As the velocity is reduced and X becomes equal to X_0, there is a sudden, marked transition and the motion becomes two-dimensional, consisting of a number of more or less cylindrical eddies, the axes of which are vertical. Viewed from the top surface the motion is mainly restricted to a continuous, wavy "jet" stream which touches first the cold surface and then the hot surface, forming a petal-shaped pattern. Provided the ratio of the radii of the inner to the outer surfaces of the convecting fluid is not too small, a pattern with two lobes can be produced (Fig. 4). Then as X is reduced first three (Fig. 5), then four (Fig. 6), and finally five lobes appear (Fig. 7)

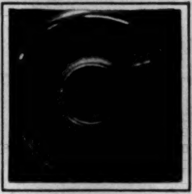

Fig. 3--Three-dimensional pattern

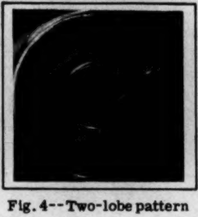

Fig. 4--Two-lobe pattern

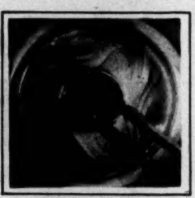

Fig. 5--Three-lobe pattern

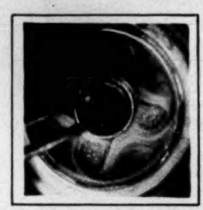

Fig. 6--Four-lobe pattern

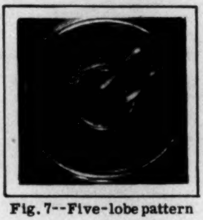

Fig. 7--Five-lobe pattern

Figures 3 - 7 were taken with apparatus in which the inner cylinder has a radius of 1.92 cm, the outer radius of the convecting fluid is 4.85 cm, and the depth d of water is 10 cm. The angular velocity w for each pattern is given in Table 2, which also lists $\Delta\rho'/\rho$, where $\Delta\rho' = \alpha T$, and where T is the difference in temperature between the hot and cold baths. Table 2 also includes the quantity $X' = d\,\Delta\rho'/w^2\rho$ which is proportional to the Rossby number. The change over between the two- and three-dimensional regimes takes place at $X' = 20 \times 10^{-2}$.

Table 2--Data on the convective patterns shown in Figures 3 - 7

Figure	Type of flow	w	$\Delta\rho'/\rho$	X'
		rad/sec		
3	Three dimensional	1.56	15.0×10^{-3}	62×10^{-3}
4	Two lobes	1.56	-4.2×10^{-3}	17×10^{-3}
5	Three lobes	3.48	-7.0×10^{-3}	5.8×10^{-3}
6	Four lobes	3.48	-4.1×10^{-3}	3.4×10^{-3}
7	Five lobes	4.71	-4.3×10^{-3}	1.9×10^{-3}

Eventually, for very low values of X the pattern, which has been a very stable one, begins to break up. It does so by a quite characteristic "vacillation," shown in Figure 8. Here are shown six successive photographs of the three-lobed pattern going in vacillation. The narrower the inner cylinder the fewer the number of lobes which can be produced without vacillation. As is seen in Figure 8, the pattern oscillates rhythmically between the continuous jet stream, though with a marked asymmetry in shape, and three curled-up eddies.

The formation of the jet stream can be understood in a qualitative way. The circulation in a convection cell of the conventional Rayleigh theory is shown in Figure 9; the velocities throughout the cell are of a similar order of magnitude. The question arises as to how the heat gets into and out of the fluid in the central streamlines. It must do so by conduction and consequently the circulation pattern shown in Figure 9 must be only applicable at such small velocities that the heat

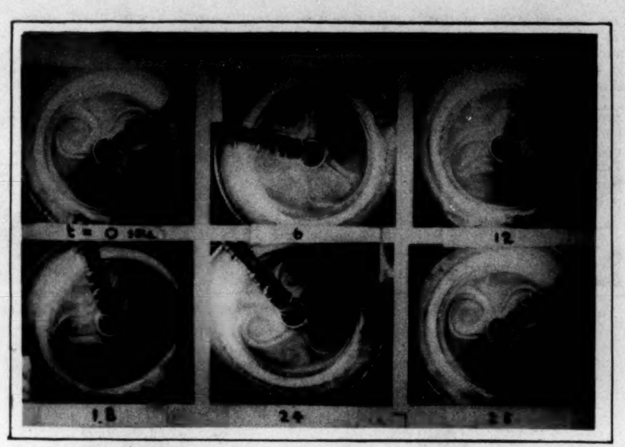

Fig. 8--Vacillating pattern with very low value of X

can diffuse over the necessary distance. The fluid will only spend a time ℓ/v, where ℓ is the cell dimension and v is the velocity, in contact with the source and sink, so that, if k is the diffusivity, the depth of penetration of the heat into the fluid will be of the order $\sqrt{k\ell/v}$ and this may be small compared to ℓ. In this case the buoyancy forces driving the convection will only cause motion in an outer periphery of the cell, provided the viscous forces are unimportant. The formation of jets in this experiment seems to arise in this way.

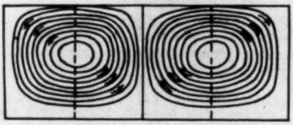

Fig. 9--Circulation in the Bénard convection system

Another feature of the experiment which is of interest is the steady rotation of the whole pattern relative to the boundaries. This is simply analagous to the well-known retrograde motion of a vortex with respect to a boundary [LAMB, 1932, chap. 7]. If the convection pattern consisted of a distribution of equal vortices, alternately of opposite sign, no drift of the pattern as a whole relative to the boundary would be expected. However, because of the dominant Coriolis force, the observed patterns have not this type of symmetry and so a drift results. At one time the author thought that this phenomenon might provide an explanation of the westerly drift of the geomagnetic field but it has recently become clear that the electromagnetic torques between the core and mantle, which must be present if electric current flows in the lower part of the mantle, are capable of causing considerable changes in the drift and may well explain it entirely. In this case it becomes impossible to infer the magnitude of the velocities in the core from the westward drift.

The "jet stream" which is produced in this experiment bears a close relation to the atmospheric jet stream and, in fact, if the inner cylinder is taken to represent the polar regions and the outer annulus the equatorial region, the jet stream is distributed in much the same way as it is in the atmosphere. Further study of such experimental models of the jet stream would seem to be of critical importance for meteorology.

While there is no reason to suppose that the circumstances which give rise to the jet stream will be absent in the core, the strong magnetic field will undoubtedly spread it out, but to what extent remains uncertain. However, the possibility of jet streams throws an entirely new light on the problem of the heat transfer in the core. The heat Q convected per second per unit area of surface by a fluid is given by

$$Q = cfvT$$

where v is the velocity of the fluid, T the temperature difference between the up-going and down-going streams at the same pressure, c the thermal capacity of the fluid, and f the proportion of the volume of fluid taking part in the convection. In the core Q can hardly be greater than the heat conducted through the surface of the Earth, of the order of 10^{-6} cal/cm^2 sec. The value of c will be about unity; thus $fTv = 10^{-6}$. Assuming that $g = 10^{-4}$, the streamlines being rather less than a kilometer wide and taking Elsasser's estimate for v equal to 0.1 cm/sec, then we find that T cannot be greater than about 1/10°. As we have indicated, we cannot be sure that the velocity v approaches in magnitude the velocity of the drift of the core on the mantle, supposing it to be mainly electromagnetic in origin. We might estimate v as follows. We have seen that the secular variation, the time scale of which is of the order of 100 years (2×10^9 sec), has its origin in changes in a thin outer shell of approximately 25 km thick, supposing that the secular variation is caused by instabilities in the jet stream near the core-mantle boundary. This gives a value for v of the order of $2.5 \times 10^6/2 \times 10^9 = 10^{-3}$ cm/sec. Consequently, T may be of the order of 10°C.

The generation of electric and magnetic modes in the Earth's core--We shall now proceed to enquire as to how the main geomagnetic field may be generated by the convection currents in the Earth's core. We have already seen that the hypothesis of electromotive forces on the core-mantle boundary seems required by the theory of the change in the length of the day. Thermoelectromotive forces would naturally be set up by the temperature differences, resulting from the convective motions, over the surface separating the core and mantle, which all geophysical evidence suggests to be a major discontinuity of physical and chemical properties. We first must investigate the type of current and magnetic-field distribution set up by this type of distribution of electromotive force.

It will be assumed that there exists across the core-mantle interface a steady electromotive force $Ae^{im\lambda} P_n^m(\theta)$, proportional to the temperature variation T over the boundary. This will produce in the inner mantle and core magnetic fields and currents of the electric mode, the components of which can be written down from Table 2 of BULLARD [1949b]. In the core the magnetic-field components, the radial component of the current, and the electric scalar potential will be, using the spherical coordinates r, θ, λ

$$\begin{aligned}
{}_r H_{nm} &= 0 \\
{}_\theta H_{nm} &= 4\pi a\ Kim\ (n+1)^{-1}\ (r/r_1)^n\ e^{im\lambda}\ P_n^m(\theta)/\sin\theta \\
{}_\lambda H_{nm} &= -4\pi a\ K\ (n+1)^{-1}\ (r/r_1)^n\ e^{im\lambda}\ dP_n^m(\theta)/d\theta \\
{}_r I_{nm} &= a\ K\ n\ (r^{n-1}/r_1^n)\ e^{im\lambda}\ P_n^m(\theta) \\
\phi_{nm} &= -a\ (r^n/r_1^n)\ e^{im\lambda}\ P_n^m(\theta)
\end{aligned}$$

and in the mantle

$$\begin{aligned}
{}_r H_{nm} &= 0 \\
{}_\theta H_{nm} &= [4\pi bK'\ im\ (n+1)^{-1}\ (r/r_1)^n - 4\pi cK'\ im\ n^{-1}\ (r_1/r)^{n+1}]\ e^{im\lambda}\ P_n^m(\theta)/\sin\theta \\
{}_\lambda H_{nm} &= [-4\pi bK'\ (n+1)^{-1}\ (r/r_1)^n + 4\pi cK' n^{-1}\ (r_1/r)^{n+1}]\ e^{im\lambda}\ dP_n^m(\theta)/d\theta \\
{}_r I_{nm} &= [bK'n\ (r^{n-1}/r_1^n) - cK'\ (n+1)\ (r_1^{n+1}/r^{n+2})]\ e^{im\lambda}\ P_n^m(\theta) \\
\phi_{nm} &= -[b\ (r/r_1)n + c\ (r_1/r)^{n+1}]\ e^{im\lambda}\ P_n^m(\theta)
\end{aligned}$$

where r_1 is the radius of the core and K and K' are respectively the conductivity of the core and inner mantle.

The boundary conditions are that the radial component of the current must vanish at $r = r_2$ (the outer surface of the lower mantle) and must be continuous at $r = r_1$.

Thus

$$bn\ r_2^{2n+1} = c\ (n+1)\ r_1^{2n+1}$$

and

$$aKn = bK'n - cK'(n+1)$$

Also

$$A = a - (b + c)$$

Thus

$$a = \frac{A\,K'(n+1)\,[(r_1/r_2)^{2n+1} - 1]}{\left\{K'(n+1)\,[(r_1/r_2)^{2n+1} - 1] - Kn\,[1 + (n + 1/n)]\,(r_1/r_2)^{2n+1}\right\}}$$

For $K' \ll K$

$$a = \frac{A\,K'(n+1)\,[1 - (r_1/r_2)^{2n+1}]}{K\,[n + (n+1)\,(r_1/r_2)^{2n+1}]}$$

Taking $r_1 = 3500$ km and $r_2 = 4500$ km, and considering the case when $m = n = 4$, $K = 1000\ \mathrm{ohm}^{-1}\ \mathrm{cm}^{-1}$, and $K' = 10\ \mathrm{ohm}^{-1}\ \mathrm{cm}^{-1}$, we obtain $a = 0.0099A$. The θ component of the field at the core-mantle boundary will therefore be $9.95\ Aie^{im\lambda}\ P_n^m(\theta)/\sin\theta$ gauss, where A is measured in volts.

Thus to produce electric-mode magnetic fields within the core greater than the dipole field, the electromotive force must be of the order of a volt or more. Our knowledge of the thermoelectromotive forces at high pressures and temperatures is negligible, but it is of interest to notice that the thermoelectromotive force of semi-conductors under laboratory conditions ranges around a millivolt/°C, approximately a hundred times greater than that of a metal under the same conditions. Nor is the theory of the thermoelectromotive force in an adequate form to predict its value at the core-mantle interface. However, it is clear that temperature differences of some hundreds of degrees may be required over the core-mantle interface. As the temperature there may be of the order of 10,000°C, this does not seem unreasonable. However, the maintenance of temperature differences of this kind requires some consideration, for the flow of electric current between the hot and cold areas will tend to equalize the temperatures by the Peltier effect. Suppose we take a thermoelectromotive force of ten millivolts/°C, then in order to produce fields of the order inferred above, temperature differences between different parts of the interface will be required of the order of 100°C. The Peltier heat emitted or absorbed per unit time equals the current times the thermoelectromotive force multiplied by the ratio of the absolute temperature to the temperature difference. The radial component of the electric current density at the interface is given by $1.13 \times 10^{-9}\ Ae^{im\lambda}\ P_n^m(\theta)\ \mathrm{amp/cm^2}$. Thus for $A = 1$, every square centimeter of the surface is absorbing or emitting about 2.69×10^{-7} cal/sec. This can be compared with the heat flow at the surface of the Earth which is about $1.3 \times 10^{-6}\ \mathrm{cal/cm^2}$ sec and the heat flow necessary to maintain the adiabatic gradient in the core calculated by BULLARD [1950] to be about $2 \times 10^{-6}\ \mathrm{cal/cm^2}$ sec.

It is not impossible that the temperature differences may originate in the widespread temperature inhomogeneities in the lower part of the mantle, the evidence for the existence of which will be discussed elsewhere. These inhomogeneities may result from slight concentrations of radioactive materials or may possibly have existed since the origin of the Earth. However, we have seen how temperature differences approaching the order of those required can arise from the type of convection which we have suggested.

It seems possible, however, that the existence of electromotive forces across the core-mantle interface of the order of those suggested above, that is, one volt, can be put to a direct test. Let us first suppose that the upper part of the mantle is an insulator. The electric mode fields in the lower mantle and core do not set up a magnetic field outside the conducting inner mantle. But due to the surface charges built up between the inner and outer mantle, an electric field of the order of 10^{-8} volts/cm exists outside, which if it can be detected proves the existence of the electric mode fields. In fact, the electrical conductivity distribution in the mantle is not well represented by the simple model that we have so far found satisfactory, but it has been shown by F. J. Lowes and P. H. Roberts that, providing the electrical conductivity of the mantle decreases continually with increasing radial distance, electric mode currents will be flowing steadily near the surface of the Earth, corresponding to potential gradients of the same order, that is, 10^{-8} volts/cm. Whether such earth potentials, which are somewhat less than those associated with the currents induced from the transient variations in the geomagnetic field, can be detected is being investigated by F. J. Lowes at the Department of Geodesy and Geophysics, Cambridge University.

We have not so far discussed how the magnetic mode fields which are observed at the surface of the Earth are generated from the electric mode. However, we have so far tacitly assumed the core to have no internal motions; this is the condition for the separation of the fields in a conducting sphere into magnetic and electric modes to be possible. When the interaction of the primary electric-mode magnetic fields with the fluid motions within the core is considered the generation of the magnetic mode becomes unavoidable. It is well known that on the scale of the core quite slow motions can greatly alter the distribution of the lines of force of the inducing field. In general, it is known that the interaction between electric-mode magnetic field and motions having radial components will produce magnetic fields of the magnetic-mode type. These interactions were considered in a general way by ELSASSER [1946b] and certain selection rules apply which in the case of these particular interactions are ones which do not vanish. Further discussion of this matter will be given elsewhere.

The evidence from palaeomagnetism--A discussion of the physical processes in the Earth's core would be incomplete without some reference to the evidence of the past history of the geomagnetic field, which is rapidly being extended by the study of the remanent magnetization of rocks. The permanent polarization of igneous and sedimentary rocks has long been the subject of investigation and reasons have been produced for believing that, in simple cases, the present remanent polarization is along the direction of the magnetic field at the time of formation.

Recent evidence, mainly from the lava flows in Iceland, seems at present to require that the mean direction of the geomagnetic field, when averaged over periods in the past greater than a few thousand years, is rather exactly that of a central dipole aligned along the geographical axis, though its polarity may not always be the same as at present. The actual process of reversal seems to take place over intervals which are of the order of the longest time of free decay in the core (several thousands of years), but it happens too quickly, geologically speaking, to be traced in any detail as yet. The time during which the polarity remains the same seems to be of the order of a few hundred thousand to a few million years.

The common interpretation of the strong remanent magnetization of lava flows and other igneous bodies depends on the low coercive force of the ferromagnetic minerals near their Curie points. Thus in cooling in a field of the order of half a gauss the rocks acquire a moment in the same direction as the field and with a magnitude approaching that of saturation. This view has recently been challenged by Néel on theoretical grounds and by Nagata from certain experimental observations. NÉEL [1951] suggested three processes by which a rock in cooling from a temperature higher than the highest Curie point of the ferromagnetic minerals present in the rock could acquire a magnetization opposite to that of the field in which it cooled, and NAGATA, AKIMOTO, and UYEDA [1951] have found a dacitic pumice in which this actually occurs. As many lava flows have actually been observed to acquire a magnetization in the same direction as the field in which they cooled, and as the vast majority of rocks when cooled in the laboratory do in fact obtain this strong thermoremanent magnetization in the direction of the applied field, it remains to be established whether the Néel-Nagata type of reversal is just a rare anomalous property of certain particular minerals with a rather restricted range of compositions and physical properties or whether the effect is capable of occurring in the field in subtle ways which cannot be easily reproduced or recognized in the laboratory and does in fact account for all the reversed magnetizations actually observed. The field evidence which we possess at present and which will now be considered does not appear to me to make the latter view plausible.

Undoubtedly the many recorded cases of rocks with reversed magnetization, observed over the last few decades, have been discounted on the prejudice that such large changes of the geomagnetic field could not occur and inherently improbable geological or physical processes were often invoked to account for them. In 1950 I realized, while examining Hospers' preliminary measurements on the Icelandic lava flows, later published [HOSPERS, 1951], that it was an extraordinary circumstance that all the magnetizations markedly different from the present direction of the Earth's field clustered round the direction exactly at 180° to it and that this was also rather generally true with respect to the older observations (see the anomalous magnetization found by BRUCKSHAW and ROBERTSON [1949] in the tholeiite dykes of northern England). This generalization seems reasonably good for rocks which are not too old, say, for Tertiary and Quarternary rocks, and hitherto its importance seems to have been neglected in discussions of rock magnetism. This circumstance rules out, of course, many of the arguments previously used to discount the straightforward interpretation of rock magnetism, such as the idea that anomalous magnetizations reflected the presence at the time of cooling of a very strong local anomaly in the geomagnetic field, which has since disappeared, or the notion that anomalous magnetizations were the result of lightning flashes. Though Bruckshaw and Robertson well demonstrated the difficulty of explaining the reversed polarity of the tholeiite dykes of northern England in terms other than that of a reversed geomagnetic field, Hospers' study of the lava flows of Iceland provides perhaps the strongest evidence yet found for the occurrence of such reversals. The lava flows of Iceland form a nearly horizontal plateau of Tertiary and Quarternary basalts, which have been deeply eroded in recent times, the flows being exposed in series in the valleys. Hospers finds that, without exception, the lava flows erupted since about 500,000 years ago - that is, the known historic flows, the post-glacial flows, and a mid-Quarternary series - are all magnetized in the present direction of the field. Yet in early Quarternary times there is a series of about 30 flows which are reversely magnetized. At one exposure there is a series of normal Tertiary flows lying beneath the Quarternary flows. Beneath this series of normal flows are a series of reversed flows. In all there seems to have been five occasions when the geomagnetic polarity was reversed.

The succession of reversed and normal zones effectively excludes wholesale overturning as an explanation of the reversals of magnetization, though geological considerations alone would rule out this possibility. What can be said about the possibility of explaining these reversed polarizations along the lines suggested by Néel and Nagata? Firstly, Hospers has done extensive reheating tests on the lava samples, cooling them from about 600° C in the Earth's field. No sample exhibits an effect similar to the dacitic pumice found by Nagata. Further, by experiments in which the specimens are only exposed to the Earth's field while cooling through a narrow range of temperature (usually 50° C), the Earth's field being cancelled out during the remainder of the cooling process, the ferromagnetic minerals present in the rock may be grouped according to their Curie points. It is always found that two main groups are present, those with a Curie point around 550° C and those with one around 250° C. Neither these experiments, nor petrological examination as yet incomplete, give any clue to suggest systematic differences in the amounts or type of the ferromagnetic minerals present in those lava samples found to be magnetized normally and those found to be reversely magnetized in the field.

Further, many lacustrine or marine sediments possess a remanent magnetization, and though this is much weaker than that of igneous rocks, it appears to have been acquired, assuming no diagenesis subsequent to deposition, by the orientation of the ferromagnetic grains, many of which being of domain size will often be spontaneously magnetized in the direction of the field during deposition. Perhaps the varved clays of New England are the best-known examples, though recent work is demonstrating that many sediments, including those of Torridonian age in Scotland, have maintained their polarization undisturbed since the time of deposition or very soon after deposition. Many examples of sediments overlying lava flows are found in Iceland and there are a few examples of intercalated sediments, where deposition of material has occurred between successive lava flows. In each case the sediments examined were found to have magnetizations, reversed and normal, which were concordant with those of the lava flows most closely contemporaneous with them. It seems hard to explain this result except by invoking geomagnetic field reversals, for though it cannot be doubted that the Néel-Nagata type of reversal may explain some of the examples of reversals found in igneous rocks and though it is possible that a similar process may be found which would give reversals in sedimentary rocks on some occasions, it would be strange if contemporaneous igneous and sedimentary rocks gave concordant magnetizations by accident.

The discussion whether geomagnetic reversals occur is beset by many pitfalls and it seems worthwhile to make some mention of them. It has been argued that as there are many fewer examples of reversely magnetized sediments than reversely magnetized igneous rocks recorded in the literature, the latter must have a cause closely associated with vulcanism. This point of view ignores the fact that magnetically unstable rocks will remagnetize in the direction of the present Earth's field and that if magnetic instability may be so common the record of the changes in the geomagnetic field may be all but wiped out. The intensity of magnetization of the ferromagnetic minerals in most sediments, unlike that of lava flows, seems to be very far from saturation; thus comparatively small amounts of magnetization since deposition may completely alter the original direction of magnetization. Thus, for example, the slight diagenesis which many old sediments have undergone may have involved sufficiently high temperature of, say, 100° C to cause the rock on cooling to acquire enough thermoremanent magnetization to wipe out the original direction of magnetization, especially since we know that many common ferromagnetic minerals have Curie points below 300° C. Again, many examples of conglomerates are known in which the magnetizations of the pebbles have been partially or entirely turned from the initial random directions to the direction of a recent field.

A further difficulty is the different time scale of geological and geomagnetic phenomena. Geological methods or radioactive dating do not enable simultaneity to be established sufficiently well to carry out the desirable test as to whether reversed magnetizations occur in rocks laid down at the same time in different localities. This fact is ignored in the comments made in the annual report of the Department of Terrestrial Magnetism for 1949-50 on the significance of a 100-foot reversely magnetized bed in the Silurian of West Virginia. It is argued that as this bed contains a rare fossil ostracod, Mastigobolbina typus, the contemporaneity of a bed containing the same fossil in the flat lying deposits at Clinton, New York, can be established. As this bed is normally magnetized it is concluded that the reversed magnetization is a local phenomenon. Quite apart from the question of magnetic stability, it is doubtful whether palaeontological evidence permits the establishment of contemporaneity to within a million years at the best. We have seen how Icelandic evidence indicates that the time during which the field has one polarity may be much less than this.

Again, the Néel-Nagata explanation suggests that a correlation may be found between certain ferromagnetic minerals and the reversed magnetization of the igneous rocks in which they occur. The discovery by BALSLEY, BUDDINGTON, and FAHEY [1952] that in metamorphised rocks of the Adirondacks there exists such a correlation, though not a complete one, between the presence of ferromagnetic minerals of composition in the range from hematite to ilmenite and the presence of reversed magnetization apparently provides direct support for the Néel-Nagata process. Though this may be a factor in the situation, there are two other possibilities. The area may, in the process of metamorphism, have been raised to different temperatures in different localities at different times. Thus it cannot be said that the magnetizations observed in the rocks were obtained at the same time. If they were not, then rocks containing the same ferromagnetic minerals and therefore having the same Curie point would tend to be magnetized at the same time. It seems at this stage to be unwise to imply that conclusions concerning the geomagnetic field can be drawn from rocks which have undergone any kind of metamorphism.

Conclusion and acknowledgments--We have seen that the polarity of the main geomagnetic field must depend on a number of possibly variable factors, while apparently the axial character of the field depends on a very fundamental feature of the dynamics of the core. The effect of the mantle in attenuating important components of the field and the theory of the changes of the length of the day both lead us to the view that the dipole field is a secondary phenomenon, the by-product of much greater magnetic fields within the Earth. Perhaps it is here that the modern developments in geomagnetism make the most distinct break with the older ideas. This framework would seem capable of accomodating the idea of complete reversals of the geomagnetic field, if this hypothesis is finally required by the evidence from rock magnetism. It will be interesting to pursue the inquiry as to what process can bring about such reversals. At present it is only possible to suggest that any large change in the pattern of the convective motion, say, a change in the number of lobes, may be a factor in changing the polarity of the field.

An attempt has been made in this paper to summarize the various lines of investigation, from which we hope to derive a picture of the physical processes in the Earth's core responsible for the phenomena connected with the main geomagnetic field. I recognize that the origin of the primary electromotive forces is a matter of some controversy and this paper and those of Elsasser and Vestine published in this colloquium together summarize the different points of view at present held. At all events there is now general agreement that the origin of the field is to be sought in the flow of electric current in the deep interior. The long period during which the possibility remained open that geomagnetism was a new property of rotating matter has apparently been ended by the negative results of experiments of RUNCORN, BENSON, MOORE, and GRIFFITHS [1951], and BLACKETT [1952].

It is a pleasure to record my gratitude to my colleagues in the Department of Geodesy and Geophysics of Cambridge University for much discussion and for permission to report on the results of their work prior to publication. I am indebted to R. Hide for providing me with the originals of Figures 2 - 8.

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DISCUSSION

E. H. Vestine (Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.)--It will be the aim here to continue the discussion of problems of the Earth's core, and especially of a few topics considered in Runcorn's interesting paper. There will first be briefly described another study of the fluctuations in the Earth's rate of rotation in relation to fluid motions of the core. Some descriptive material on current systems within the Earth will then be indicated, and discussed in relation to fluid motions near the surface of the core. These are of interest in the ELSASSER [1950]-BULLARD [1949] theories of the geomagnetic field. The effect of fluid motions in the core upon the shape of the Earth and the main longitudinal gravity term will be mentioned very tentatively for possible consideration of geodesists. Finally, a few remarks will be made about an interesting and simple Hall-current generator of the geomagnetic field which has intrigued Tuve, Tatel, and me at the Department of Terrestrial Magnetism for the past year.

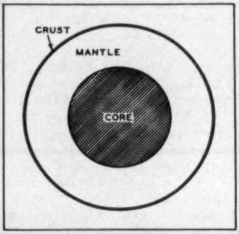

Fig. 10--The three major parts of the Earth

Figure 10 shows a view of the core, introduced here merely to illustrate the three major parts: the crust, the more or less solid mantle, and the core. You will have noted from Runcorn's paper that the core is usually regarded as the seat and source of the geomagnetic field, though another obscure region, the lower half of the mantle, is sometimes mentioned. Of course, a little comes from crustal rocks. The Earth's magnetic field closely resembles that due to a large magnet imbedded in the central core about 200 mi from the Earth's center. The latter displacement is in the general direction of the Dutch East Indies. If then for any reason the Earth's core should start rotating faster than the outer part of the Earth, at the Earth's surface the magnetic field of the imbedded magnet would be seen to rotate faster than the Earth's surface. The Earth's magnetic field as a whole would then be found traveling around to the east. Conversely, if the core rotated more slowly than the Earth's surface the Earth's magnetic field would then be observed drifting off to the west.

Figure 11 shows the successive five-yearly positions of this dipole in latitude and longitude from 1830 to 1950 as found from spherical harmonic analyses of the Earth's magnetic field. If the dipole is replaced by an equivalent thick electric current sheet flowing in the surface of the core, the five-yearly positions trace the approximate locus of a point in the outer part of the core from 1830 to 1950. This follows from magnetohydrodynamics [ELSASSER, 1950; BULLARD, 1949], or Maxwell's equations, since the electric conductivity of the core should be high (about 3×10^{-6} emu) and the linear dimensions large (of the order of thousands of km); accordingly, this electrical current sheet would be pretty well locked in position in the surface layers of the core. Attention should be called to the close spacing of the five-yearly points near 1910, which shows that the rate of northwesterly motion of the particular point in the surface layer of the core was substantially less than that for years after 1925. In fact, according to Figure 11, a pulse of about 60 years' duration appeared in the northwesterly drift in the magnetic field measured at the Earth's surface. It would be possible to see this pulse at the Earth's surface only if the current layer in the core were at a shallow level, and the electric conductivity of the lower mantle of the order 7×10^{-9} emu.

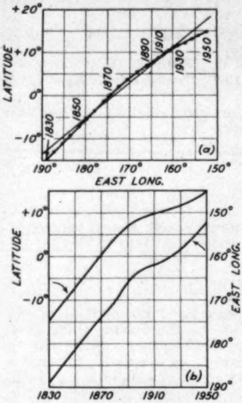

Fig. 11--(a) Motion of eccentric dipole 1830-1950, and (b) its latitude and longitude, 1830-1950

Prior to about 1900 the geomagnetic data were so sparse that the five-yearly spacings could at most give an indication of the average northwesterly motion. For convenience, the dipole used here is the eccentric dipole, and its successive locations in position with time rest heavily on the spherical harmonic term P_2^1, because the P_1^0 and P_1^1 terms also used define the centered dipole; the centered dipole does not seem to have changed much in orientation in the past 100 years. The harmonic P_3^1 shows similar indications, and this is satisfying since the precision of its determination, as in the case of P_2^1, depends largely on values of the Earth's horizontal surface field averaged half way around a parallel of latitude.

The fluctuating core motions just deduced on the basis of the experimental data are confirmed in a most remarkable way. In simple terms we may summarize the results of Figure 11 as follows: The measurements show that the pattern of the Earth's field has moved westward at an average rate of about 20 km per annum at the equator. Since 1890 the measurements of the magnetic field have been better and more complete, and have sufficed to show that the westward motion of the core relative to the Earth's surface in fact slowed up to just a few km per annum near 1910. This, of course, means that the core of the Earth was rotating faster than before because it almost caught up to the rotation of the outer part of the Earth in 1910. To conserve momentum the outer part has then to rotate more slowly. This is precisely what BROUWER [1952] seems to have found from astronomical data on the rate of the Earth's rotation, shown in Figure 12b, as compared with (a) taken from Figure 11. After 1910, when the core gradually slowed down, the outer part of the Earth speeded up. Thus the fluctuating core motions just deduced are independently checked, and simultaneously afford an unforced explanation of the major problem of the fluctuations in the Earth's rate of rotation [MUNK and REVELLE, 1952a; VESTINE and LANGE, 1952, 1953].

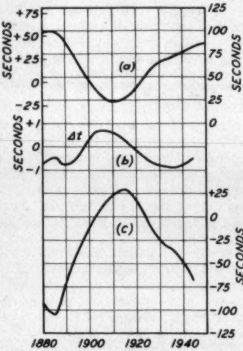

Fig. 12--Fluctuations in eastward drift velocity of (a) outer core, (b) Earth's crust, and (c) inner core

There is also the possibility of an additional check. It is found that the westward drift of the magnetic field is accompanied by a related fluctuating northward motion of the field and of the core on the side of the Earth centered near the Dutch East Indies, with southward motion on the opposite side. The outer part of the Earth will then move with respect to the core, which means that the north pole of the Earth moves off the Earth's axis of rotation in a direction parallel to the equatorial axis of the core motion. Since the changes in angular momentum applied are of internal origin, the axis of rotation must of necessity remain fixed meanwhile relative to the stars. Accordingly, the crust and mantle will move to conserve angular momentum so that the north pole of given epoch moves off the axis of rotation. Its predicted motion due to this cause will be towards North America near the meridian 270° east longitude from 1910 to 1940, by an amount probably of five to ten feet with a slight drift to the west due to the westward core motion meanwhile. This agrees with some results of astronomy, but it does not necessarily agree with others. In fact, it is not quite clear that the actual variation of latitude is known at all for the period from astronomy. Moreover, HOSOYAMA [1952], and also MUNK and REVELLE [1952b], have shown that changes in sea level, and the melting of glacial ice should also provide north polar motion, possibly of similar type and amount. Accordingly, this independent check on the core motions cannot be quantitatively established. The most that can be said is that the core motions do not predict for the period of interest a greater north polar motion than that observed by astronomers. However, the westward drift of the Earth's field, together with the dynamical check with the Earth's rotation, are satisfying evidence of material motion. It will be recalled that similar conclusions, based partly on the geomagnetic data presented, were reached by **MUNK** and **REVELLE** [1952a], using a slightly different analytical treatment. Of course, it must be confessed on the experimental side that there has been an inverse matching of only a single 60-year pulse in crustal motion with a similar pulse in core motion, so that future observations are desirable. There are also some questions about probable errors in measurement which could benefit by more adequate treatment than can be attempted here.

There is a difference in interpretation between Runcorn's treatment and that of 1952 papers by Munk and Revelle and myself which assume Bullard's model of the core in the rough quantitative checks. However, the implication that the core is susceptible of fluid motion is the same in both treatments, and the estimates of electric conductivity of the mantle also come out about the same. When Runcorn completes his calculation of the electromagnetic couples between core and mantle, it should then be possible to determine from the fluid motions just described, the magnitudes of the poloidal and toroidal fields required.

The non-dipole part of the geomagnetic field; that is, the part excluding the centered dipole, will next be considered, because it is natural to hope that it may afford an analogous means of depicting the local average motions within a surface layer of the core, additional to the average motion already deduced around a great circle. There has as yet been little success in deducing such motions. However, since the raw data of geomagnetism are of interest in core problems today, it seems desirable to include a few descriptive features here, motivated by the interest in fluid motions.

One of the simplest ways of representing the geomagnetic field and its secular change is that afforded by a fictitious current system flowing in a thin shell concentric with the Earth. Figure 13 shows such a current system at depth 3000 km, deduced from spherical harmonic analysis of the surface field [**VESTINE** and Others, 1947ab]. It will reproduce the non-dipole part of tne main field for 1945 within a few per cent. Even though this be so, the finer and possibly even some of the grosser details in current pattern so deduced are likely to be erroneous.

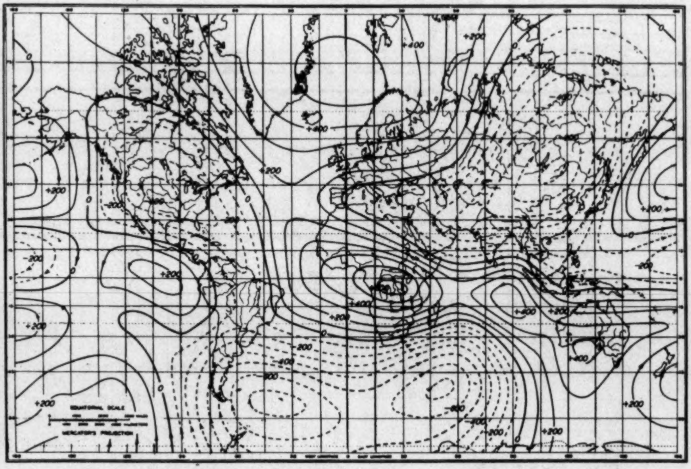

Fig. 13--Current function in 10^6 amperes for thin spherical shell at depth 3000 km within Earth to reproduce residual (non-dipole part) of main field, epoch 1945

Figure 14 shows the corresponding yearly changes in the current pattern calculated in Figure 13, at four epochs ten years apart, plus the smoothly distributed currents due to the dipole terms

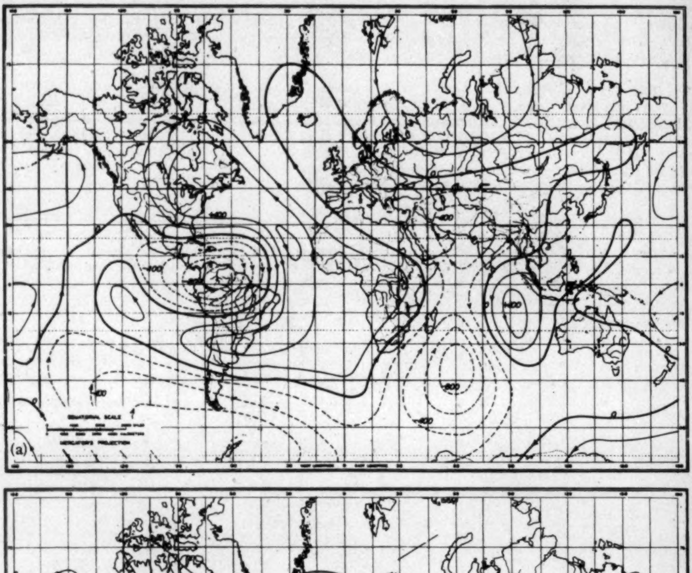
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Fig. 14--Current function in 10^4 amperes for thin spherical shell at depth 3000 km within Earth to reproduce geomagnetic secular change, (a) epoch 1912.5 and (b) epoch 1922.5

in the current function. However, inclusion of the latter current functions should not greatly alter the qualitative character.

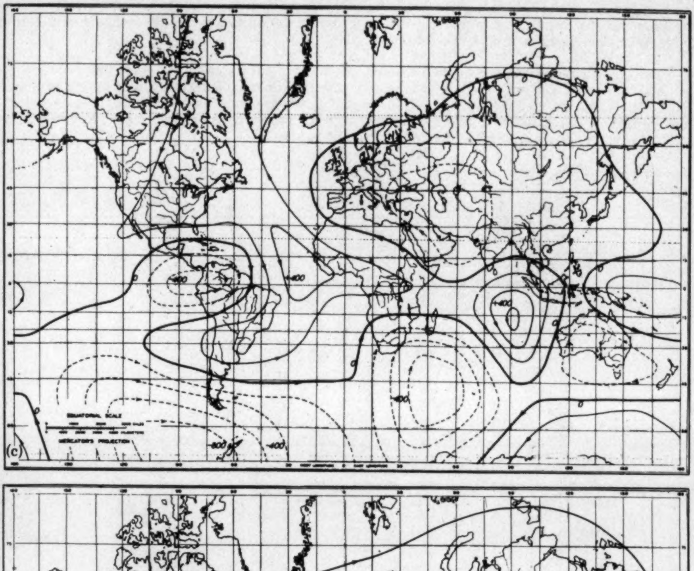
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Fig. 14--Current function in 10^4 amperes for thin spherical shell at depth 3000 km within Earth to reproduce geomagnetic secular change, (c) epoch 1932.5 and (b) epoch 1942.5

Unfortunately, there are two grave sources of error in Figures 13 and 14. A major source of error is in the extrapolation of high-degree terms; for instance, a term of degree 6 in the current function at the Earth's surface would probably introduce an error several times as great at the surface of the core as that for a low-degree term. It is also possible that the extrapolation has been carried into a region where important sources of field may be present, especially due to electromagnetic induction in the lower mantle.

The current functions for depth 3000 km only include terms up to and including degree and order 6; in view of the supposed unfavorable conditions for extrapolation it may be surprising to find so little evidence of violent oscillation of the higher degree terms with latitude or longitude. Accordingly, it is not unlikely that extrapolation to the more modest level of 2000 km below the Earth's surface may really provide information of value.

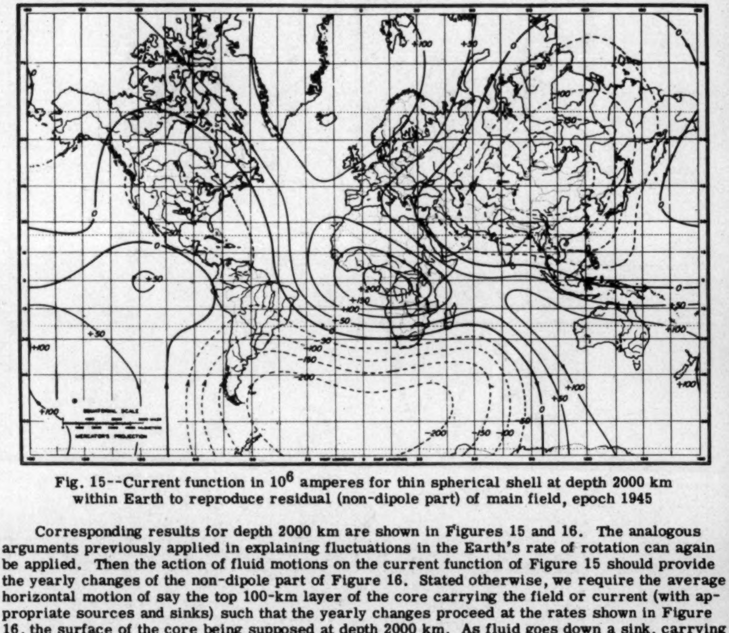
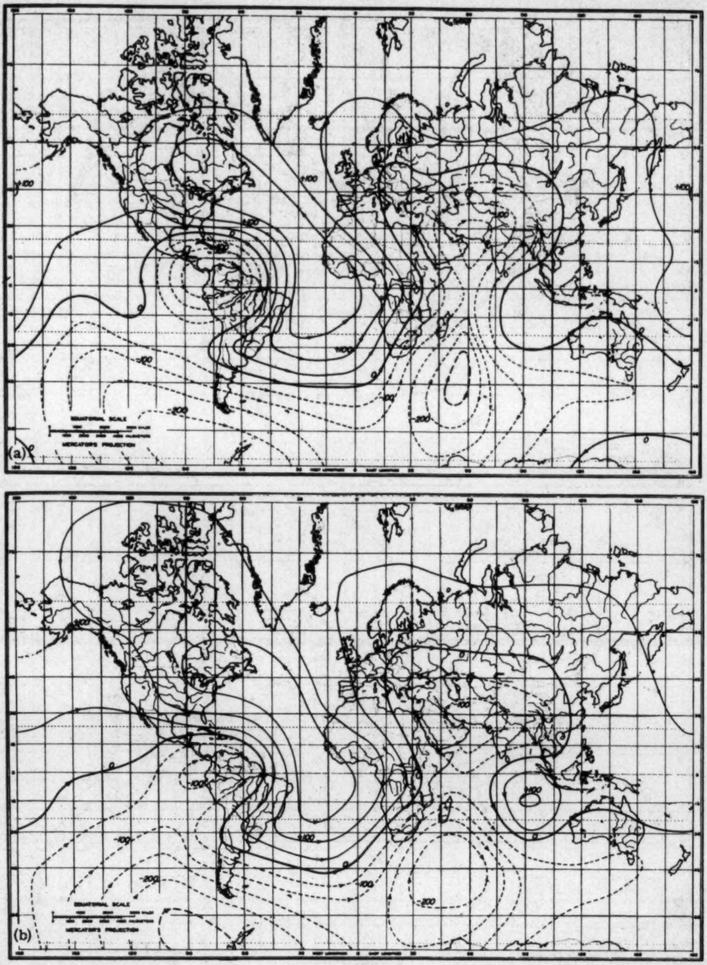


Fig. 15--Current function in 10^6 amperes for thin spherical shell at depth 2000 km within Earth to reproduce residual (non-dipole part) of main field, epoch 1945

Corresponding results for depth 2000 km are shown in Figures 15 and 16. The analogous arguments previously applied in explaining fluctuations in the Earth's rate of rotation can again be applied. Then the action of fluid motions on the current function of Figure 15 should provide the yearly changes of the non-dipole part of Figure 16. Stated otherwise, we require the average horizontal motion of say the top 100-km layer of the core carrying the field or current (with appropriate sources and sinks) such that the yearly changes proceed at the rates shown in Figure 16, the surface of the core being supposed at depth 2000 km. As fluid goes down a sink, carrying the magnetic field and source along, the effects of vertical motion will be powerfully screened by the highly conducting surface layers of the core.

Only some incomplete work on this problem can be reported here. To date, the results are highly speculative rather than factual, but not without some note of encouragement. If just west of South America there is imagined a sink in the surface layer of the core it will have been acting on the counterclockwise current of Figure 15 there, carrying this current downwards from view. This is qualitatively the same as the adding of clockwise circulations of current shown for 1912.5, 1922.5, 1932.5, and 1942.5. The rate of addition would be more rapid in 1912.5 when the currents of Figure 15 were stronger. Conversely, if fluid is rising in the surface of the core just west of Central Africa, building up the clockwise focus of current there (Fig. 15), the additions per year shown in Figure 16 should be in the same sense, which appears to be the case. Just west of Sumatra, Figure 15 would have shown a clockwise circulation in 1912; with a sink in fluid there the anticlockwise foci of Figure 16 would result. A symmetrical center of rise in fluid might be looked for in the central Pacific, but if present the changes per annum in current are evidently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EQUATORIAL SCALE
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EAST LONGITUDE
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-100
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-100
-200
-200
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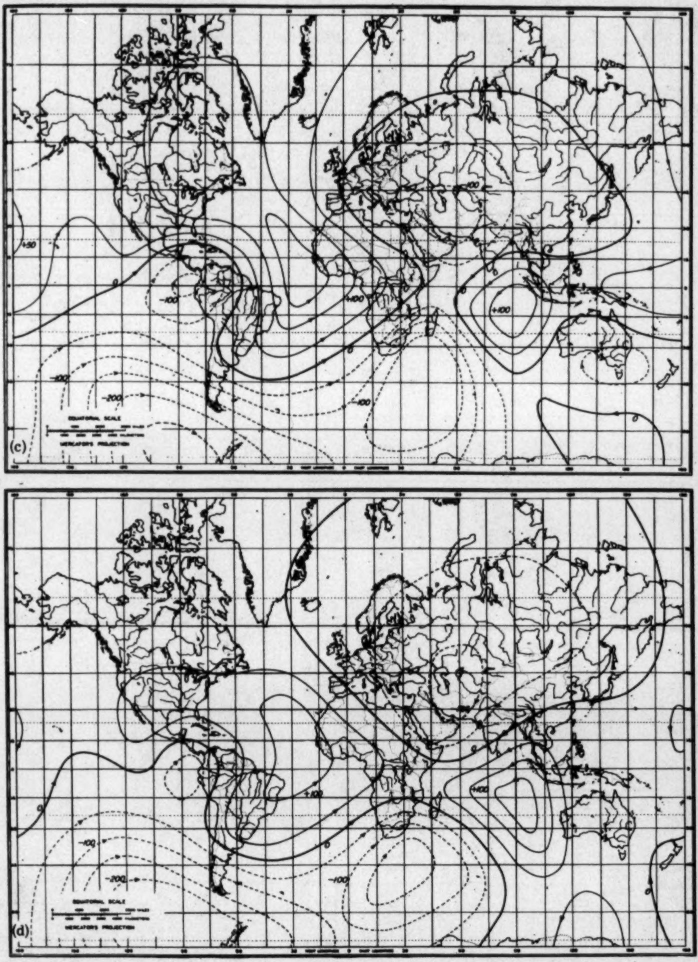
EQUATORIAL SCALE
MERCATOR'S PROJECTION
WEST LONGITUDE
EAST LONGITUDE
(b)

Fig. 16--Current function in 10^4 amperes for thin spherical shell at depth 2000 km within Earth to reproduce geomagnetic secular change, (a) epoch 1912.5 and (b) epoch 1922.5

very small, as are also the residual currents there (Fig. 15). In the same way it may be possible to estimate the motions of the core for other isoporic foci.


+50
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EQUATORIAL SCALE
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(c)
(d)

Fig. 16--Current function in 10^4 amperes for thin spherical shell at depth 2000 km within Earth to reproduce geomagnetic secular change, (c) epoch 1932.5 and (d) epoch 1942.5

It should be stated that the remarks just made are purely illustrative, and that actual estimates were made of horizontal motions using pairs of magnetic-field components. Those made using the vertical component did not provide satisfactory checks with those obtained using the north and east components of the residual field. This failure may be due to a lack of attention to effects of electromagnetic induction in the mantle which should reduce the observed horizontal components, and augment the vertical component with the vertical component less satisfactory; a brief paper discussing this effect of electromagnetic induction in the mantle has been prepared together with Price. Some part of the main dipole-producing currents may be modified also by the surface fluid motions.

It is obviously very desirable (because unique inferences cannot be drawn from magnetic data alone) that some dynamical check be found as in the case of fluctuations in the Earth's rate of rotation. There seems only a remote hope of this. The most direct possibility is that rising and falling centers of fluid near the surface of the core are accompanied by sufficient radial stress to slightly alter the shape of the Earth. In fact, JEFFREYS [1952] has already found some evidence for a small P_2^2 term in the Earth's gravitational field, in fair agreement with the phase requirements with longitude just conjectured. It might be worth while to look for time fluctuations in the gravitational field if suitably stable tilt meters or gravimeters can be designed. Accordingly, it is reasonable to hope that something can be learned ultimately about the more detailed core motions near its surface.

Finally, mainly to stimulate discussion, mention will be made of an hypothesis of the origin of the dipole component of the Earth's main field that Tuve, Tatel, and I have been discussing for some time at the Department of Terrestrial Magnetism. At the Department of Terrestrial Magnetism we have never distinguished ourselves by developing a theory of the Earth's main field which we did not later manage to tear apart. However, I will mention one idea additional to that of the dynamo theory of Elsasser and Bullard which may merit careful consideration. This is the idea that toroidal fields are necessarily accompanied by a substantial Hall current in the mantle. We have not spoken much of Hall currents in the core, since Hall coefficients in a molten metal have never been observed, and because a dipole field within the core is likely to be wound up mainly into toroidal fields in any case by the westward relative motion of the core with respect to the mantle.

Ordinarily a Hall current i_H in a conductor flows at right angles to a primary current and field and is given by

$$i_H = R\,I\,H_0\,K \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where R is the Hall coefficient, I the primary current, H_0 the primary magnetic field, and K the electric conductivity. Now the size of i_H depends directly on R and K, for a given I and H_0. R may be as great as 400 in a semi-conductor but is likely to be of the order of unity or less in metallic conductors. Runcorn has mentioned that the core is probably a semi-conductor, and hence may have a Hall coefficient as great as unity as a modest understatement. Elsasser and Bullard have shown it is rather easy to generate toroidal currents; the difficulty has been to find out how to make the fluid of the core move in the toroidal field in such a way so as to generate a dipole-producing set of currents. Now maybe the dipole field is there anyway due to the Hall currents flowing in the mantle; the oppositely directed Hall currents in the core may be weaker or nonexistent in the molten metal.

It has been suggested that such Hall currents would be regenerative. For instance, imagine the north polar area of the core to be cold at its junction with the mantle, and the south polar area hot. Then thermoelectric currents may flow within meridian planes, yielding a set of toroidal currents. If the northward flowing current in the mantle is I and there is present an axial dipole field H, however small, a Hall current in the direction $\vec{I} \wedge \vec{H}$ (perpendicular to I) is expected. These Hall currents will flow along parallels of latitude, and in an opposite sense in the northern and southern hemispheres. The field generated will be of quadrupole type. (In the oral presentation of this discussion it was erroneously stated that this Hall field was of dipole type.) If we complicate the situation slightly by supposing both polar junctions to be cold and an encircling equatorial junction hot, rising toroidal currents from core to mantle may appear at the equator returning corewards near the poles. In the presence of a weak dipole field like that outside the Earth the Hall currents will then be directed westward in both northern and southern hemispheres, increasing the original weak dipole field. The original weak dipole field, if due to a thin spherical current sheet flowing in the base of the mantle or surface of the core, would have a uniform axial field inside equal to $-2H_0$ and a field is approximately equal to H_0 just outside the current sheet in the equatorial plane. Then from (4)

$$i_H = R\,I\,H_o\,K \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

and if $R = 1$, $K = 10^{-9}$ for the mantle $i_H = 10^{-9}\,H_o\,I$.

Now for the thin spherical current sheet flowing at the base of the mantle, say, the increase in current corresponds to an increase h in H_o outside, given by about $4\pi i_H/3$. A mechanical force $\vec{I} \wedge \vec{H}$ may serve to keep the currents close to the core at the equator as they are generated and decaying, in addition to diffusion of current corewards occasioned by a steep conductivity gradient. Actually the field $-2H_o$ inside the core is likely to have its lines of force inside the core more or less wound up into toroidal fields, because of the westward drift, thus minimizing possible Hall currents in the molten core.

Accordingly, (5) becomes $h = \alpha H_o$, where $\alpha = (4\pi/3) \times 10^{-9}\,I$, approximately 10^{-9}, say. Since h is in the direction H_o, it will add to the original field H_o. Thus if $h_1 = \alpha H_o$ is generated over an interval of time short enough so that H_o can be regarded as constant, $h_1 = \alpha H_o$, $h_2 = \alpha(H_o + h_1)$, $h_3 = \alpha(H_o + h_1 + h_2)$, ... If the current increments i_H migrate corewards, they will be likely to decay at a slower rate than that at which they are generated. If this be so, the original dipole field may be considerably amplified, even though α is small. It would hence be of interest to find a solution of Maxwell's equations appropriate to this problem.

The foregoing supposed $I = 0.25$ amperes, per cm width of vertical section, a value of similar order to that considered by Bullard and Elsasser. It seems likely that the Hall currents therefore may contribute significantly in the generation of magnetic fields in the mantle. Accordingly, it provides a relatively simple mechanism whereby the toroidal fields can be converted into poloidal fields forming the field observed at the Earth's surface. Formally, the dynamo equations that Bullard and Elsasser have endeavored to solve would therefore include an additional term corresponding to the Hall conduction term.

The effects of Hall currents may be both generative or degenerative. A multiple toroidal current, in a primary field, may simultaneously contain Hall currents reinforcing the primary field in one region while reducing it in other latitudes.

Finally, the possibility of an accessible check of toroidal fields on a geophysical scale should be mentioned. In the ionized region of the upper atmosphere there is considerable evidence of zonal winds. Calculations in progress show that these will yield toroidal fields in the atmosphere when the velocity of the zonal wind varies with height. These fields might be quite large, especially near the auroral zone, but it is not clear that they can provide fields in excess of the Earth's surface field, for example, within homogeneous auroral arcs. The most obvious method of detection would be through the use of rocket or radio measurements, since leakage of toroidal fields to ground level would be small.

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W. M. Elsasser (University of Utah, Salt Lake City, Utah)--The reality of the connection between fluid motions in the Earth's core and the phenomena of the geomagnetic secular variation is now rather well established. The exhaustive evaluation of the secular data by VESTINE [1948], showing in such a spectacular fashion the detailed, rapidly varying structure of the field, and the theory of the westerly drift motion by BULLARD and Collaborators [1950] have put this interpretation of the geomagnetic variation on a sound physical basis. The dynamo theories go one step further. They assume that not only is the geomagnetic field modified by the motions of the conducting liquid in the core, but that these motions can themselves generate and maintain a magnetic field. This viewpoint [ELSASSER, 1947] has been greatly strengthened by a number of discoveries in astronomy that indicate a close relationship between the motions of electrically conducting cosmic fluids and magnetic fields. Many stars have now been shown to have magnetic fields of several thousand gauss; some stars have alternating fields that change their sign every few days. There is, moreover, good evidence for the existence of magnetic fields in interstellar gas clouds. Together with the data on solar and sunspot magnetic fields, these observations constitute a body of evidence in favor of the ubiquitous existence of magnetic fields in electrically conducting fluids of large dimensions. In stellar or interstellar gases the electrical conductivity is attributed to ionization; in the Earth's core it is due to the metallic character of the fluid. In the geomagnetic case there might also exist certain driving electric forces such as thermoelectric emf's, as has been pointed out by Runcorn. One can advance a long ways in the understanding of terrestrial and stellar magnetic fields by investigating the dynamics of the interaction between fluid motion and field without the assumption of a driving emf. These interactions which can be formulated in terms of the differential equations of classical physics have been studied in recent years by a number of authors under the name of magneto-hydrodynamics [LUNDQUIST, 1952]. The dynamo theories in particular assume that the maintenance of the geomagnetic field may be explained by magneto-hydrodynamics alone.

The basic phenomenon is the deformation of a magnetic field, existing in a conducting fluid, by the motion of the fluid. In an ideal conductor the magnetic lines of force are permanently attached ("frozen") to the individual particles of the fluid. Actual fluids have sufficiently high conductivity to be treated approximately as ideal. If the fluid undergoes a shearing motion the spacing of the lines of force will in general change. The lines of force may become more closely packed, in which case the magnetic field energy residing in that part of the fluid is increased (amplification), or else they may become more widely spaced (decrease of the field energy, deamplification). The mathematical analysis shows that the required amount of energy comes from, or goes to, the kinetic energy of the fluid motion. The system as a whole behaves so that its mechanical degrees of freedom are supplemented by the degrees of freedom of the electromagnetic field, the two being closely coupled to each other so as to form essentially a single dynamical system whose study is the object of magneto-hydrodynamics.

It is characteristic of these phenomena that they appear significantly only in large dimensions. The criterion may be formulated by saying that the loss of magnetic field energy by thermal dissipation must be slower than the average rate of transfer of the energy from the mechanical motions into the field. Mathematically speaking, a certain non-dimensional quantity which is altogether analogous to the ordinary Reynolds number must be large [ELSASSER, 1950]; in fact, the condition for turbulence in the fluid expressed by a large Reynolds number and the condition for strong magneto-hydrodynamical coupling are frequently so similar as to be almost equivalent. Thus if a cosmic fluid is turbulent and at the same time exhibits a good electrical conductivity, we might expect to find magnetic fields. In the Earth's core these conditions are fulfilled.

The dynamo theory, then, assumes that the magnetic field in the core is maintained by amplificatory processes which draw their energy from the fluid motion. This presumes that the motions in the core are maintained by some other source, and thermal convection is generally considered the most likely mechanism. Again, two rather distinctly different views may be taken regarding the model of a dynamo. One type of model assumes as a first approximation to reality a quite regular type of fluid motion. It may be shown that an extremely simple pattern of motion, for example, one with rotational symmetry, will not yield steady amplification, but more complicated patterns will do so. One such pattern has been studied in much quantitative detail by BULLARD [in press]. It consists of a core with a non-uniform angular velocity of rotation (an effect which results from convective vertical transport) together with four vertical currents which are centered on four equidistant points of the equator and which are alternately rising and sinking. The questions of the stability of such a motion and of the reaction of the field upon the motion are not raised; it is assumed that this model represents an idealization of the type of motion which we perceive in the geomagnetic secular variation. Bullard has succeeded in showing that such a motion can maintain a steady magnetic field as against the thermal dissipation of the electric currents. It is characteristic of this mechanism that the main part of the magnetic field thus produced is confined entirely within the core; the lines of force of this field component, designated as the toroidal field, are internally closed and run along the circles of latitude. The toroidal field has opposite direction in the two hemispheres. It is much stronger than the magnetic dipole field which we perceive at the outside of the core.

Another view of the amplificatory processes in the core takes as its start the models developed in the statistical theory of turbulence. It is well known that in a turbulent fluid the energy is first contained in the largest eddies, whence it is distributed gradually into smaller and smaller eddies, to be eventually dissipated by viscosity. In the course of this process, stray magnetic fields in the fluid may be amplified, but the final result must not be considered from the viewpoint of individual amplificatory processes, but from an overall, statistical view. It may be assumed that as a result of the competitive amplificatory and de-amplificatory processes an average statistical distribution of the energy results in which a certain fraction of the total energy has become transformed into electromagnetic field energy. It is then not necessary to assume special mechanical constraints that provide for the amplification; instead, the presence of magnetic field is attributed to the natural statistical tendency of the energy to spread as widely and as evenly as possible, a phenomenon familiar to any student of kinetic theory and statistical thermodynamics. Again, the possibility of the energy's spreading into the electromagnetic field is bound up with the extremely large Reynolds numbers found in large-scale cosmic fluid masses such as the Earth's core, and would be difficult to demonstrate in the laboratory with the much smaller Reynolds numbers attainable there. A dynamical theory of these phenomena is still lacking (so is a satisfactory theory of turbulence for that matter) but CHANDRASEKHAR [1951] has succeeded in an extensive kinematical analysis which is essentially an extension of the well-known von Karman-Howarth theory of turbulent correlations to the magneto-hydrodynamical case.

In this turbulent generator model it must be assumed that the magnetic fields in the core are closely correlated to the individual eddies and, in some form or other, follow their patterns. This would explain the irregular magnetic field observed, but leaves the origin of the dipole field open to conjecture. It is unlikely that the eddies in the core are oriented at random, on account of the relatively overwhelming magnitude of the Coriolis force in the dynamics of these motions. Thus, if the eddies are statistically correlated to the Earth's axis, the same may be expected of their related magnetic fields, and an average field having rotational symmetry approximately about the Earth's axis might result. A mathematical attack upon this difficult dynamical problem has not yet been made. Again here, the dipole field appears rather as a secondary effect resulting from the modification of much stronger magnetic fields inside the core. This seems a characteristic feature of the dynamo type of theory of geomagnetism which we have already encountered in Bullard's models. It is much too early to judge from our as yet most incomplete dynamical understanding of the dynamo models whether they would admit of a reversal of the Earth's dipole moment in the geological past such as is indicated by the interesting data presented in the preceding paper by Runcorn. Future work of this kind will no doubt soon lead to a final decision as to whether such reversals have repeatedly taken place in the course of the Earth's history. In any event, a dynamo model based on a statistical assembly of eddies could perhaps account for such reversals as an effect of statistical fluctuations, and it is therefore difficult to deny categorically the possibility of such a reversal on the basis of a dynamo theory. It would in particular not be necessary to assume that the dipole component of the field is reversed throughout the interior of the core. It would suffice to assume that a reversal is the result of an eddy fluctuation in a relatively thin layer near the surface of the core; such a fluctuation would then not affect the dynamo mechanism in the deeper layers.

It is a fairly safe guess that a more realistic dynamo theory must be intermediate between the stationary model with regular large-scale features indicated previously and the purely statistical model just discussed. One is here reminded of the problem of the general circulation of the Earth's atmosphere which in many dynamical aspects is closely similar to the problem of the fluid circulation in the Earth's core. In spite of nearly a century of efforts no fully satisfactory model of the atmospheric circulation has as yet been developed. It is controversial as to whether the general circulation drives the large eddies, or conversely, or whether there is any distinct sense to this question at all. This writer believes that progress in these two most difficult dynamical problems is likely to be parallel, and that no easy solutions can be expected in any case, and perhaps no rigorous dynamical analysis will be forthcoming for a long time.

One further aspect of the problem should be mentioned here which is closely related to the turbulent character of the motion. In a turbulent fluid all transport phenomena are profoundly modified. The eddy conductivity takes over the role of the molecular conductivity in such phenomena as heat conduction, mixing of impurities, viscous stresses, and so on. There can be little doubt that the same must apply to the dissipation of electric currents, which effect will be greatly enhanced by the eddying motion. There is some empirical evidence for this: If the core were a ball of solid iron, an electric current flowing in it would take about 20,000 years to decay spontaneously (after the manner of free decay of current in an induction coil which is short-circuited). Observation shows that all components of the Earth's magnetic field vary with time, including the dipole moment of the Earth itself which has decreased by five per cent in magnitude in the course of the past century. All such fluctuations seem to involve periods of the order of a few centuries, 2000 years at the most, and the discrepancy with the larger figure calculated for decay in a conductor at rest must no doubt be accounted for by the motions connected with the internal eddy structure of the core.

Let us finally return for a moment to the question of electromotive forces acting upon the core. In view of the rapidly varying eddy configuration it is unlikely that any emf's acting entirely within the fluid of the core would give rise to appreciable electromagnetic effects. Also, simple calculations show that convective motion will result from exceedingly small inhomogeneities within the fluid whose electrical effects would be negligible. The question is different for emf's acting at the boundary of the mantle and the core. Such might, for instance, be thermoelectric forces acting between the polar and the equatorial regions of that boundary. Since half of such a circuit is through the weakly conducting mantle, the resulting average current is essentially determined by the resistance of the mantle and would be largely independent of the electromagnetic conditions within the eddying core. The magnetic field generated would be of the toroidal type with opposite sign in the two hemispheres. While a pure dynamo theory based entirely upon the amplifying properties of the fluid motion seems attractive to this writer, the possibility of such impressed emf's playing a certain role in the mechanism of the Earth's field cannot as yet be ruled out at the present state of our knowledge.

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John W. Graham (Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.)--I believe that some will recall that, based on our observations in sediments in the Appalachian area and in sediments outside the geosyncline, we proposed a few years ago that there may be some mechanism by which a direction of remanent magnetism of a rock may become reversed as a result of some clever process of nature that takes place independent of the prevailing Earth's magnetic field. This inversion process is now known to take place in some igneous rocks and in some synthetic compounds, but all the details of the phenomenon are not yet understood.

In the summer of 1952 and the winter of 1952-53 we studied some Michigan Precambrian diabase dikes with inverse magnetizations, and as a result of this work we were able to propose a hypothesis [GRAHAM, 1953] by which it may be possible to interpret the inverse magnetizations of these dike rocks as resulting, not from a reversed Earth's field, but from a combination of straightforward physical and chemical processes taking place within the rock.

One particularly significant manner of behavior of the ferromagnetic ingredient of these rocks was noticed (Fig. 17). When this material is heated only briefly to 600° C, it undergoes a rather striking mineralogical alteration of a sort that must have an important influence on the magnetic behavior. This alteration is so profound that it seems reasonable to conclude that it is not possible by laboratory heating experiments to learn about the behavior of this particular rock at the time it originally was injected. This conclusion is at variance with the accepted practice of believing that heating experiments give a realistic indication of the original thermomagnetic behavior of igneous rocks.

One aspect of the hypothesis is that it should be possible for sediments which have ferromagnetic material of appropriate constitution to have their remanent moments undergo the self-reversal

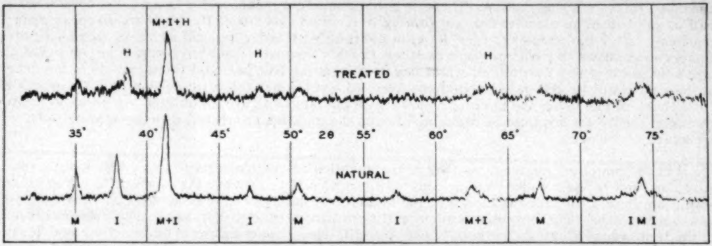

Fig. 17--X-ray diffraction spectra (Co Kα radiation) of natural and heat-treated magnetic fraction; M = maghemite ($\gamma\ Fe_2O_3$) and magnetite (Fe_3O_4) or both; I = ilmenite ($Fe\ Ti\ O_3$); H = hematite (αFe_2O_3)

process. This self-reversal would be favored by temperature elevation and an oxidizing environment. Runcorn mentioned a case in Iceland where a series of lava flows with normal polarizations were invaded by a dike having inverse polarizations. You will recall that the normal flows, in the vicinity of the dike, had inverse polarizations, and he pointed out that the simplest thing to believe is that the Earth's magnetic field was reversed at the time this dike was injected. On the basis of our hypothesis, the dike material had the appropriate constitution and history to favor its self-reversal of magnetization, and the normal polarization flows acquired their local inverse magnetizations under the influence of the elevated temperature and oxidizing conditions promoted by the dike. In other words, the magnetization mechanism of inverse rocks can be treated as a dynamic multiple-step process calling for a particular sequence of events and particular constitution. I would suggest that this sequence of Icelandic flows with normal polarizations had latent within them the self-reversal property, and I would predict that a dike with normal polarizations cutting through these flows would also cause their local self-reversal of polarization. This is a critical field experiment that, if made, should provide a basis by which to select the better of the proposed ways of interpreting the mechanism by which these rocks become magnetized.

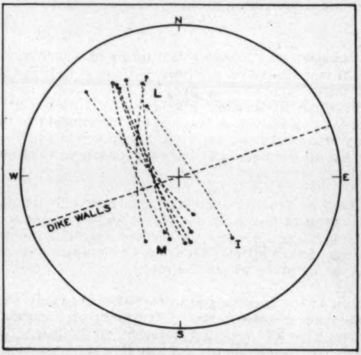

Fig. 18--Directions of principal axes of magnetic susceptibility; L = least susceptibility axis; I = intermediate susceptibility axis; M = maximum susceptibility axis

I would like to discuss one further point of the rock magnetism data that Runcorn presented. You will recall that in some of the exposures the observed magnetizations showed appreciable scatter of direction. I infer that this scatter is attributed to small local disturbances which are imagined to be unbiased in direction so that the data can be averaged and a final significant direction chosen. Undoubtedly movements can disturb directions of magnetization. In our work last summer, however, we were able to show that there must be additionally, some other explanation for scattered magnetizations in some rocks. In Figure 18 you see the pattern for the directions of the maximum and minimum elongation axes of the ferromagnetic minerals in a dike, plotted on the lower hemisphere of the equal area projection. This pattern we attribute to primary injection flow phenomena, and you see that there is no strong suggestion of disturbance of the material. The observed magnetizations (Fig. 19), however, are grossly scattered when all the points are considered, but show some tendency toward a smooth variation of inclination from point to point as the dike is traversed. Very tentatively we attribute this variation to changes produced in the composition of the melt by temperature gradients at the time of injection. Thus, in this case, a statistical mean might be subject to various difficulties of interpretation.

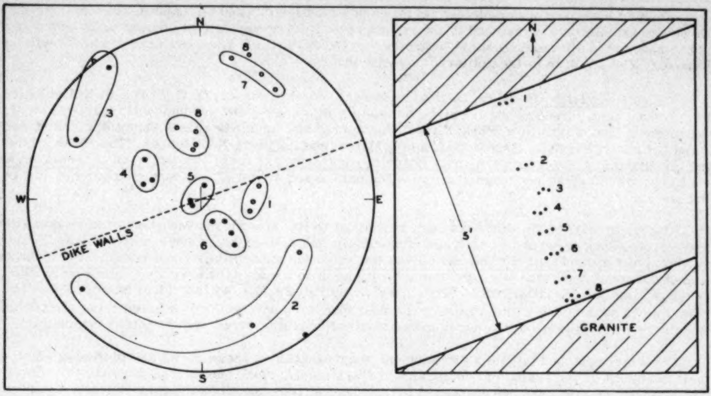

Fig. 19--Magnetizations observed at selected sites in 5' diabase dike;
• = N-seeking magnetization; o = S-seeking magnetization

In summary, I look on the problem of rock magnetism as an exceedingly complex one in which we probably do not yet know all the variables. In my opinion, the contention that the Earth's field has reversed on a number of occasions in geologic time has not been adequately substantiated.

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L. W. Morley (Box 44, Billings Bridge P. O., Ottawa, Ont., Canada)--For the purpose of inferring the directions of the geomagnetic field at various times during geological history, the choice of rock formation selected for study is very important. It would seem that Runcorn's group made a happy choice in the selection of Icelandic lava flows. These rocks, because of their rapid cooling and consequent fineness of grain, possess a high coercive force and are thus able to retain their original thermoremanental directions with great tenacity. Bruckshaw's results in the tholeiite dikes of northern England and Graham's in diabase dikes are considerably more scattered in their polarization directions and are therefore not as suitable for this particular study.

As I now know, I made a particularly bad choice of rock for my thesis study at the University of Toronto. The Grenville gabbros which I investigated had such a low coercive force that the mere dropping of a cube of this rock on the floor would in some cases change the polarization direction. Most samples, however, evidently withstood the effect of cutting with the diamond wheel because in each case a number of contiguous cubes cut from the same hand specimen gave the same polarization directions. Samples taken from within a foot or two of each other generally varied by as much as 30° or 40° while at separations of six to seven feet, remanence directions would often be at variance by as much as 180°. It seemed as though there existed a sort of macroscopic magnetic domain structure within the outcrops.

Because they were able to repeat measurements of remanence directions within single lava formations, Runcorn's group have demonstrated that they were measuring remanence which must have been influenced only by the uniform field of the Earth and that directions were not seriously affected by any local disturbing forces either during cooling or later.

Whether the cases of completely reversed polarization directions found in the Icelandic lava flows are explained by a reversal of the geomagnetic field at the time of cooling or by some such phenomenon as antiferromagnetism is another matter. Partially inverted remanence directions, however, lend no force to the antiferromagnetic theory.

James R. Balsley, Jr. (U. S. Geological Survey, Washington 25, D. C.)--The U. S. Geological Survey has been investigating negative anomalies discovered by aeromagnetic surveys in the Adirondack Mountains, New York; Upper Peninsula, Michigan; Bearpaw Mountains, Montana; Fairfax County, Virginia; Aroostook County, Maine; and northern New Jersey. The rocks producing the anomalies are igneous or metamorphic, ranging in age from Precambrian to Triassic, and all have reverse remanent magnetization. The nature and origin of this magnetization is now being studied.

The major part of the work has been restricted to the Adirondack Mountains where more than 200 oriented specimens of normally and abnormally magnetized rocks have been collected. The chemical and mineralogical composition and the magnetic susceptibility and remanent magnetization of the specimens have been determined. It has been found that the rocks contain magnetite (Fe_3O_4), ilmenite ($FeTiO_3$), rutile (TiO_2), and hematite (Fe_2O_3), as individual grains and as intimate intergrowth of one within another. In most instances one mineral is in the form of exsolution lamella or blebs within another but in some cases solid solution of one within another is indicated.

If the direction and intensity of remanent magnetization of these rocks are plotted against their chemical or mineralogical composition, a systematic relationship can be readily observed. The intensity of remanent magnetization per percent of iron and titanium oxide minerals is highest and its direction is most nearly opposite that of the present Earth's field in rocks whose oxide minerals are mixtures of hematite and ilmenite. These rocks also exhibit a coercivity in excess of 400 gauss and a ratio of remanent magnetization to induced magnetization as high as 2000.

Where magnetite and mixtures of hematite and ilmenite occur together in different ratios, the magnetic properties are such as to indicate normal remanent magnetism for the grains of magnetite and reverse remanent magnetization for the grains of mixed hematite and ilmenite. Rocks containing pure magnetite have a remanent magnetization in the direction of the Earth's field and have a ratio of remanent magnetization to induced magnetization less than one. Rocks containing pure hematite or ilmenite have not been encountered, but a few containing nearly pure minerals indicate that hematite and ilmenite have remanent magnetization in the direction of the Earth's field.

These data lead to the conclusion that the reverse remanent magnetization of these rocks is caused by the inherent properties of the grains of intimately mixed hematite and ilmenite which they contain. This conclusion has been verified by heating above the Curie point one specimen containing the hematite-ilmenite mixture and cooling it in the Earth's field. It was found to possess remanent magnetization opposite to that of the impressed field.

The excellent work of Runcorn and Hospers on the Icelandic lavas has led them to the conclusion that the reverse remanent magnetization of these rocks has been produced by a reversal of the Earth's magnetic field. It does not seem likely that the reversal in the Adirondacks can be explained by this means, for the masses of rock showing reverse remanent magnetization are randomly distributed over an area of several thousand square miles containing rocks whose remanent magnetization is normal. The whole area has suffered regional metamorphism during which both types of rocks were subjected to temperatures in excess of the Curie temperatures, so both normal and abnormal rocks must have been subjected to essentially the same magnetic environment while being cooled through the Curie temperature. It has been suggested that all the rocks might have originally possessed reverse remanent magnetization produced by a reversed Earth's field but that the magnetite, because of its low coercivity, has lost its original magnetization and been remagnetized in the present field. The hematite-ilmenite mixture, on the other hand, because of its high coercivity might have retained the original magnetization. The extremely high ratio of remanent magnetization to induced magnetization of the hematite-ilmenite mixtures makes it seem unlikely that these rocks could have been magnetized in a reversed Earth's field unless it had an intensity several hundred times the present field. Furthermore, the specimen which has been heated and cooled does not exhibit this property.

Néel has proposed two methods by means of which mineral grains might become magnetized in a direction opposite to that of the impressed field. We are now endeavoring by means of heating experiments on rocks of known chemical and magnetic properties to determine if either method can explain the peculiar behavior of the rocks showing reverse remanent magnetization.

THE EARTH'S MANTLE

ELASTICITY AND CONSTITUTION

Francis Birch

Abstract--The principal facts contributing to modern ideas of the structure of the mantle will be briefly reviewed. Particular attention will be given to the problem of a physical interpretation of the seismic velocities and their variations with depth, following a method discussed in detail in a recent paper by the author in the Journal of Geophysical Research (Elasticity and constitution of the Earth's interior). The principal conclusions are (1) that the mantle as a whole is not homogeneous; (2) that there may be a reasonably homogeneous layer between the depths of 900 and 2900 km, consisting of high-pressure phases, presumably of the composition of a ferromagnesian silicate; (3) that gradual changes of composition, of the proportion of high pressure phases, or both, take place in a transitional layer between the depths of 200 to 900 km. Discovery of the nature of this transitional layer is considered to be of crucial importance for dynamical geology and petrology.

The major problems of geology and geophysics lead us rather quickly to the Earth's interior, to the problem of its present constitution and of the chemical and physical processes which account for its activity. No doubt most of you feel, as I do, that this is a very durable problem; we shall have to return to it again and again, with new information and with new methods of interpretation. But, difficult and elusive as this question is, and despite the many valuable lines of evidence provided by other sciences, it presents a scientific commitment for which geophysics is particularly responsible. The most detailed information is derived from seismology, and it is mainly this information and its possible uses which I shall discuss. The spectacular achievements of Elsasser, Bullard, Vestine, Runcorn, and others [see note regarding References at end of paper] in finding, at last, a function for the Earth's central core in the production of the magnetic field and its variations have already been presented, and I shall speak only of the mantle, so far as is possible. Most of what I have to say has been published, but I welcome this opportunity for describing briefly a line of approach which seems most fruitful to me, and the principal conclusions, as of the moment. It is hardly necessary to mention that these conclusions can, and doubtless will, be questioned on various grounds.

Until some 50 years ago, the principal sources of information about the Earth's interior were geodesy and astronomy. The mean density and moment of inertia were known, and there were estimates of the effective rigidity based on the study of Earth tides. Since the mean density is about 5.5, as compared with values usually less than 3 for surface rocks, and the moment of inertia is about 1/3 MR^2, as compared with 2/5 MR^2 for a sphere of uniform density, it has long been clear that there must be an increase of density toward the center; these two pieces of information just determine such two-parameter relations between density and radius as those of Laplace and of Roche. As calculated by Kelvin, the effective rigidity was somewhat greater than that of steel, a result in conflict with the prevailing geological concept of his day, which was of a generally liquid interior covered by a thin crystalline "crust."

The first calculations based on a definite physical picture of the interior seem to be those of Wiechert, though Dana and others had earlier suggested the main features: Wiechert divided the interior into two uniform parts, a central sphere of iron, and a shell composed of heavy silicates. This subdivision was suggested by the most striking fact about meteorites, that they are chiefly composed of two distinctly different materials: silicates, and metallic iron. Iron is by far the most abundant of the heavy elements, not only in surface rocks and meteorites, but also in the outer layers of the Sun and other stars; its existence in the meteorites as free metal is a definite suggestion for a metallic core in the Earth. Wiechert's model has been greatly modified by later work, but, in principle, no better solution has been found for the gross chemical composition.

With the development of instrumental seismology, facts began to accumulate regarding definite levels inside the Earth. The central core postulated by Dana and Wiechert was now discovered to have physical reality, though its size, as later determined by Gutenberg, was very different from that of Wiechert's core. The division, based upon seismic observations, at the Oldham-Gutenberg discontinuity, is the major feature of the Earth's internal structure. The outer part, the mantle, is characterized by two distinct velocities of wave propagation, V_P and V_S, as shown in Figure 20; these have been identified with the two velocities characteristic of the ideal isotropic elastic medium. These velocities vary with depth, but throughout the mantle maintain a ratio very similar to that in familiar materials; the quantity known as Poisson's ratio is always between about 0.27

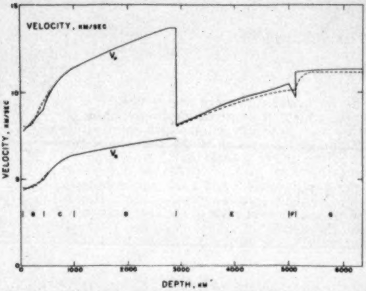

Fig. 20--Seismic velocities in the Earth's interior; solid lines, after Jeffreys; broken lines, after Gutenberg; designation of layers after Bullen

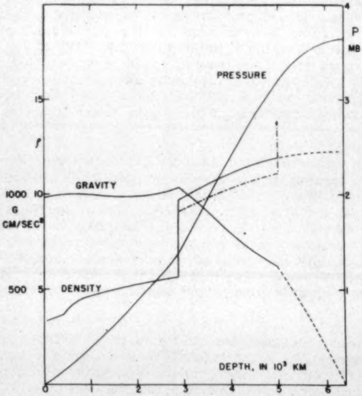

Fig. 21--Density, pressure, and acceleration within the Earth, after Bullen

and 0.30. In the core, on the other hand, a single velocity is recognized and identified with the V_P of compressional waves; the absence of V_S or of shear waves is the principal reason for supposing that most of the core is fluid, though this conclusion is supported by studies of Earth tides and of the variation of latitude.

The gradual refinement of the velocity distributions, of which recent versions are shown in the figure, made it possible to deal with a point neglected by Wiechert: the effect of pressure in changing the density. In 1923, it was remarked by L. H. Adams and E. D. Williamson, in the course of their classical studies of the compressibility of rocks, that the seismic velocities could be used to obtain the change of density with depth. Their method has been applied by Bullen, with successive recalculations reflecting improvements of the velocities. Having the density, we can then obtain the distribution of gravity and pressure throughout the interior, as shown in Figure 21, taken from Bullen's work.

The Adams-Williamson equation is found as follows: The ratio of incompressibility K to density ρ for an isotropic elastic body is

$$K/\rho = (dP/d\rho) = V_P^2 - 4/3\ V_S^2$$

We suppose that the hydrostatic relation holds with adequate approximation

$$dP = -\ g\rho dr$$

where g is the acceleration at radius r. Combining these relations, we have

$$d\rho/dr = -\ g\rho/(V_P^2 - 4/3\ V_S^2)$$

Once we have the velocities as function of radius, it is possible to integrate numerically from surface to center to obtain the whole density distribution, which must, of course, satisfy also the conditions on mean density and moment of inertia.

There are two important assumptions implicit in this method: First, it is supposed that the density changes only as a result of compression, with no change of intrinsic density, as by introduction of new material; second, the compression is supposed to be adiabatic, that is, the rate of change of temperature with depth is taken to be just the change corresponding to adiabatic compression; this follows from the use of the adiabatic incompressibility given by the seismic velocities. Since there are only two conditions upon the density distribution, we can determine at most two parameters: if we consider that there are only two distinct uniform regions, mantle and core, in each of which the Adams-Williamson relation applies, then the problem is just determinate. In this case, for any choice of density at the top of the mantle, we may solve for the density jump at the boundary of the core; this seems the natural place to have a discontinuity of density, since it is also the locus of a discontinuity of velocity. Not all of these solutions are acceptable, however, if indeed any one of them is, and I would like to emphasize an argument due to Bullen which has not been given the attention it deserves.

On Bullen's first application of the Adams-Williamson method in 1936, he began with the assumptions that the mantle was uniform in composition, and that the density at the top of the mantle was 3.32 at a depth of 33 km. A small and conventional correction was applied for the crust, which is quite unimportant in this problem. There are several reasons for this choice of initial density: it is close to the density of the magnesium-rich olivines which were believed to constitute the mantle, and to the mean density of the Moon, which is considered by some to be uniform, relatively uncompressed material similar to that of the Earth's mantle. However, on carrying through the computation to the boundary of the core, Bullen found that the remaining mass and moment of inertia to be attributed to the core alone were such that the ratio I/MR^2 for the core had the value 0.57. This would mean a concentration of mass toward the outer margin of the core, since the value of this ratio for a thin spherical shell is 2/3, and for a sphere of uniform density, 2/5. Even a uniform density in the core is inadmissible; there must be compression, and the velocity shows a steady increase down to the small and relatively unimportant inner core. Consequently it was necessary to increase the moment of inertia of the mantle, and Bullen met this requirement by introducing a discontinuous increase of density at a depth of 350 km, at which Jeffreys had introduced a discontinuous increase of velocity for independent reasons. This discontinuity was later changed to a second-order one, that is, a discontinuity of slope, but the principal conclusion remained the same: the mantle could not be uniform in composition, with its density determined by compression alone, as given by the Adams-Williamson method and the velocities now accepted.

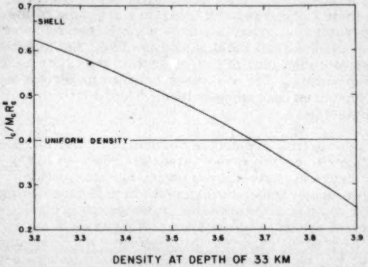

Fig. 22--Moment of inertia of the central core, as function of density at the top of a uniform mantle; I_c, M_c, and R_c are the moment of inertia, mass, and radius of the core, respectively

It might be supposed, however, that this conclusion depends upon Bullen's choice of 3.32 for the initial density. On repeating the calculations, with some unimportant simplifications, for initial densities between 3.2 and 3.9, I find the results plotted in Figure 22. The curve shows the ratio I/MR^2 for the core, as function of initial density at the top of the mantle, on the assumption that the change of density in the mantle is determined by compression alone, as given by the seismic velocities. In order to get an acceptable solution, the initial density would have to be about 3.7. Allowance for a rate of rise of temperature with depth greater than the adiabatic gradient increases the required initial density still further.

Now we do not know the density below the crust, but there are reasons for thinking that 3.7 is too high. The seismic velocities just below the crust are about 8.0 to 8.2, and 4.5 to 4.6 km/sec. Such velocities exclude an olivine rock of density 3.7, which would necessarily be iron-rich; a rock containing a large fraction of garnets, such as eclogite, would be a possibility, but this choice would commit us to an entire mantle of eclogite, which seems improbable in terms of chemical abundances. It seems highly probable, therefore, that Bullen's conclusion remains valid, even though we may wish to modify somewhat his original choice of initial density.

Thus we have to face the following question: If the density in the mantle is not determined by compression alone (with an appropriate correction for temperature effects, if required), what are the alternatives? There appear to be three: Somewhere in the mantle there must be either (1) a change of composition, involving a change of intrinsic density; or (2) a change to phases of higher density, or (3) changes of both of these kinds. A phase change of olivine from its familiar orthorhombic symmetry to a cubic, spinel structure has been suggested by Bernal and Jeffreys: this seemed particularly appropriate when it was believed that there was a first-order discontinuity of velocity at about 400 km. But this has now become at most a second-order discontinuity, and there are reasons, which I wish now to discuss, for thinking that the required abnormal density increase is not localized at a single level, but spread over a thick zone.

In principle, at any rate, we may approach this question by setting up an equation giving the rate of change of velocity or of compressibility in an ideal uniform layer, and comparing this with the observations. I have taken the quantity K/ρ, or ϕ for short, the ratio of adiabatic incompressibility to density, which is given by the velocity distribution. With the usual assumptions of reversibility of changes of pressure and temperature, it is possible to obtain a relation between the rate of change of ϕ with depth in this ideal uniform layer and various parameters of the material, and this rate of change can be compared with the observed rate of change. The theoretical relation has been developed for an arbitrary temperature gradient, so that, again in principle, it is possible to estimate the effect of departure from the adiabatic temperature distribution. The rate of variation of ϕ with depth in the ideal uniform layer is given in terms of certain dimensionless parameters of the material, involving chiefly the rate of change of incompressibility with pressure, but also thermal expansion, specific heat, and their temperature and pressure coefficients. The usefulness of this procedure depends, of course, upon the possibility of estimating these parameters for a material known only through its seismic velocities.

The examination of these coefficients leads us to a review of the theory of solids and of the extensive results of high-pressure investigation; I can give only the barest summary. One of the first points to examine is the characteristic temperature, a concept of fundamental importance in the theory of solids. This temperature plays an important part in the Debye theory of specific heat; roughly, it separates the classical, or high-temperature, region from the quantum-mechanical, or low-temperature, region. It is related to the vibrational frequencies of the crystalline lattice, which, in turn, depend upon the velocities of the elastic waves. From these velocities, with an assumption concerning the mean atomic weight of the material of the mantle which cannot be far wrong, we can obtain the Debye temperatures as function of depth in the mantle. These temperatures are everywhere lower than what seem to be minimum estimates of the temperatures; even at the base of the mantle, the Debye temperature is only about 1000°C. Thus it appears that we have to do with high-temperature properties, in spite of the marked increase of characteristic temperature produced by the high pressures of the interior. This means that we are especially interested in measurements on materials above their Debye temperatures; or since most of the measurements have been made at ordinary temperature, in materials having low Debye temperatures, such as the alkali metals, the more compressible alkali halides, and the like. Let us notice also that the Debye theory of specific heats is based on the idea of corresponding states, or a universal reduced curve of specific heat versus temperature. The difference between materials depends upon the value of a single parameter, the characteristic temperature. This relatively simple theory is successful for a great variety of materials.

We have next to see whether there is any way of getting around the obvious difficulty that our experiments do not reach sufficiently high pressures to permit direct investigations with likely materials. The laboratory pressures are by no means negligible, even on the planetary scale; Bridgman has measured the change of volume of a large number of materials to pressures as high as 100,000 bars; this is roughly the pressure at a depth of 300 km in the Earth, or the central pressure of the planet Mercury, or twice the central pressure of the Moon. What is even more significant is that many of these materials have been compressed by ratios greater than the compression at the base of the mantle, which is about 1.4; this is the ratio of compressed to uncompressed density. These large compressions show that there is a close approach to a common law of compression for a wide variety of elements and compounds. Figure 23 shows the measurements for the most compressible solids, the alkali metals, several of which have been compressed to twice their initial densities. The pressures have been reduced by dividing, in each case, by the appropriate initial incompressibility, K_0 (strictly, by $(3/2)K_0$); this is the only adjustable

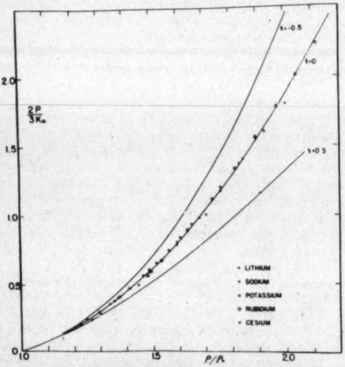

Fig. 23--Compression of the alkali metals; experimental points, after Bridgman; the smooth curves are theoretical, with several values of the parameter ξ

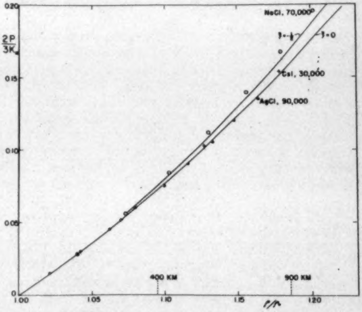

Fig. 24--Compression of several compounds; experimental points, after Bridgman; theoretical curves as in Figure 23 parameter. The five metals follow the same reduced law of compression, whose theoretical expression is given by the solid curve marked $\xi = 0$. The quantity ξ is a second adjustable parameter, not necessarily zero, though evidently it cannot be large for the alkali metals; the theoretical curves for $\xi = 1/2$ and $-1/2$ are also plotted. Figure 24 shows a similar plot for several ionic compounds, on an enlarged scale; here it appears that for NaCl, the parameter ξ is nearly -1; while for AgCl and CsI a small or zero value is adequate. These compounds also are of very different compressibilities: CsI is compressed as much at 30,000 bars as is AgCl at 90,000. Nevertheless, the experimental values show a strong similarity when reduced in this way. The compressions in the mantle, if considered uniform, at depths of 400 km and 900 km are indicated at the bottom of the figure. A great many compounds have been studied by Bridgman to higher compressions than these values. Most of the results, except for the very numerous cases where polymorphic transitions occur, can be represented within the experimental uncertainty by curves of the type shown here, with the parameter ξ seldom greater in absolute value than about 1/2. Thus we have an indication of what we may take to be the normal value of the parameter dK/dP, which is the principal factor governing the rate of variation of ϕ in a uniform layer. If $\xi = 0$, $dK/dP = 4$ at zero pressure, and gradually decreases toward about 3 for the compressions at the base of the mantle. If $\xi = -1/2$, dK/dP is 4.7 at zero pressure, and gradually decreases toward about 3.5 at the base of the mantle.

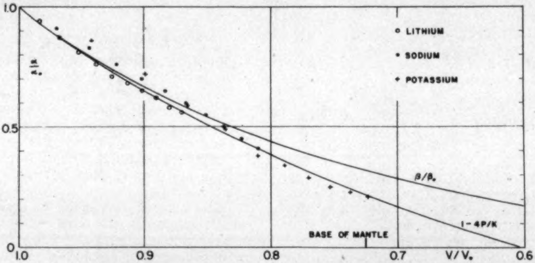

Fig. 25--Thermal expansion of the alkali metals as function of compression; experimental values after Bridgman

Another indication that the compression rather than the pressure is the most important variable for determining the high-pressure properties of solids is shown in Figure 25, where I have plotted the thermal expansion, relative to the zero-pressure value, versus compression for three alkali metals. These difficult measurements, by Bridgman, were carried to 20,000 bars in all three cases. The thermal expansion decreases by very appreciable fractions as the metals are compressed, but the results for all three metals are probably consistent with a single law of variation.

We now proceed to a comparison of the seismic values for the variation of ϕ with the theoretical curve for an isothermal uniform medium at a moderate temperature; the theoretical curve is plotted for $\xi = 0$ (Fig. 26). The open circles are derived from Jeffreys' 1939 velocities, the solid dots from Gutenberg's 1948 velocities. This comparison is the basis for several conclusions: First, we can now identify the region which departs from uniformity as lying between about 300 and 900 km, where the deviations from the theoretical curve are most extreme; second, below about 900 km, though there is some scatter, the seismic values are everywhere close to the theoretical curve. Not much can be said at present about the region shallower than some 300 km; there are still some differences of interpretation which affect the velocities. It is possible, however, that this region is nearly uniform.

This approach furnishes independent support for Bullen's conclusion with respect to the departure from uniformity of the mantle as a whole, and it furnishes additional details. We may now replace the former assumption of uniformity for the deeper part of the mantle with something resembling a demonstration of uniformity. The small discontinuity of velocity formerly placed at 400 km or so now appears as a part of a much larger abnormal increase of velocity, extending over a depth of 500 or 600 km. From the close agreement between observed and theoretical values in the lower part of the mantle, we obtain a rough indication that the temperature is not excessively high, perhaps not more than about 4000°C. On the other hand, some may prefer to believe that the appearance of uniformity arises from a set of compensating factors, such as changes of temperature just offsetting changes of composition; we have no way of demonstrating that this is impossible, however unlikely it may seem.

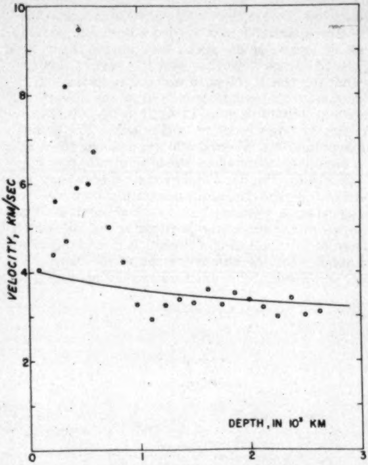

Fig. 26--The function, $1 - g^{-1}\,\Delta\phi/\Delta r$, for the mantle, versus depth; the circles are obtained from the seismic velocities; open circles, after Jeffreys; solid circles, after Gutenberg; the smooth curve is the theoretical value of (dK/dP), for $\xi = 0$

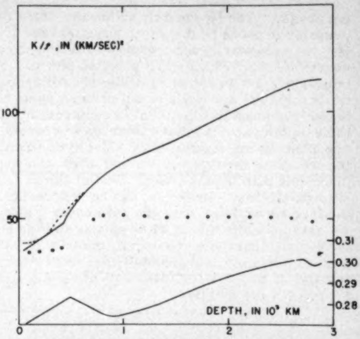

Fig. 27--The variation of K/ρ, $(K/\rho)_0$, and Poisson's ratio σ, in the mantle; the solid curve at the top gives K/ρ formed from Jeffreys' seismic velocities; the dashed curve from Gutenberg's velocities; the open circles show $(K/\rho)_0$ (the value at zero pressure) derived from the observed K/ρ at the corresponding depth; the lowermost curve shows σ, after Jeffreys

Accepting these results as indicating uniformity of the deeper mantle, we can draw some further consequences regarding the properties of this material. A point-by-point calculation leads from the observed values of K/ρ, plotted as a solid curve in Figure 27, to the zero-pressure values of K/ρ, plotted as circles. These values are closely the same below 900 km, since this is another test of uniformity, and give for this ratio at zero pressure the value 51 (km/sec)^2. This figure also shows the curve of Poisson's ratio. The reversal of trend between 400 and 900 km seems to support the conclusion already reached on other evidence concerning the departure from uniformity in this region. Let us now examine the zero-pressure values of K/ρ for some familiar materials (Table 3). The experimental values are all for ordinary temperature; the comparable value for the deep mantle might be close to 60 (km/sec)^2 The values for the common silicates are much lower than this; the olivines are far too low. There appears to be no known material with a plausible composition which has also the required value for this ratio.

Table 3--Properties at one atmosphere

Material	Density ρ_0	$(K_T/\rho)_0$
		(km/sec)^2
Corundum	4	69
Beryl	2.8	67
Rutile	4.2	50
Periclase	3.6	47
Garnets	3.5-4.2	40-45
Jadeite	3.3	39
Forsterite	3.3	36
Anorthite	2.8	33
Fayalite	4.1	26
Iron	7.9	21
Albite	2.6	20
Quartz	2.7	14

We are thus brought back to the idea of high-pressure modifications, of which so many have been discovered by Bridgman. The hypothetical spinel form of olivine has been mentioned; its properties are still unknown. There is no convincing reason for supposing that the whole mantle has the composition of olivine, however; if we are to be guided by the chemical composition of the stony meteorites, we should take roughly equal parts of olivine and pyroxene. More generally, we probably ought to think of a system with at least three major components, say MgO, FeO, and SiO_2, with the possibility of forming, at high pressure, compounds or structures with quite different properties from the known representatives of this system. Since corundum, periclase, and rutile do possess elastic properties of about the right magnitude, it is at least plausible that there may be phases in the magnesia - iron oxide - silica system with the required properties. Here we encounter a most promising area for both theoretical and experimental chemical physics, or high-pressure mineralogy, which evidently needs further study.

If this deep layer below 900 km is uniform in composition and phase, as these considerations suggest, how might it have reached such a condition? There are at least two possibilities: It might have been uniform initially, and stayed uniform, differentiation having affected only the shallower levels; or it may be a uniform product of a process of differentiation which has affected the whole mantle. For several reasons, all inconclusive, I incline toward the second alternative, but I shall not attempt to go further into this question at present.

With high-pressure phases required for the deeper part of the mantle, the region between about 300 and 800 km is most naturally interpreted as transitional between the region of familiar, low-pressure phases, just below the crust, and the deep region where the transformation to high-pressure phases has become complete. The present analysis indicates that chemical change alone is not adequate to explain the properties of the deeper part of the mantle, but chemical change in the transitional layer can evidently not be excluded, and almost any theory of the transitional layer seems to lead to a compositional gradient in this region. It seems most likely to me that we shall have to face the complex problem of a multicomponent system with pressure, temperature, and compositional gradients, as well as high-pressure phases.

There are additional reasons for looking upon the region in which this transitional layer has been found as the seat of important geophysical or geochemical processes. Earthquakes originate as far down as 700 km, deep in the transitional layer; it seems natural to associate these deep shocks with the postulated phase changes, and to predict that about 800 km will prove to be the upper limit of focal depth. It is perhaps more than a coincidence that the rate of cooling by conduction to the surface is expected to be most rapid at present between about 400 and 600 km. The formation of denser phases may be dependent upon such cooling, with the result that the amount of contraction available for "shortening the crust" may be appreciably greater than is usually estimated in terms of the classical thermal contraction process. Deep-seated fracturing associated with these density changes, and expressed as deep-focus shocks, may provide a mechanism for the extrusion of material from deep to shallow levels. These are all no more than suggestions; they require more serious examination, but they indicate a few of the possible implications of this conception of the structure of the mantle. In my opinion, the transitional layer is the key to the problem of what is going on in the mantle; when we understand its nature, we shall be well on the way to a grasp of the dynamics of the Earth's interior.

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For additional details and complete bibliography, see J. Geophys. Res., v. 57, pp. 227-286; 1952; also Bull. Geol. Soc. Amer., v. 64, pp. 601-602, 1953.

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PETROLOGICAL EVIDENCE ON TEMPERATURE DISTRIBUTION IN THE MANTLE OF THE EARTH

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Abstract--On the assumption that convection is an effective process of heat transfer in the mantle, petrological evidence suggests that the temperature at the core boundary fluctuates, in space and time, between a lower limit of about 1500° C and an upper limit of 2500° C. Generation of basaltic magma in the upper 100 km of the mantle is readily explained if the temperature gradient required to start convection does not exceed 0.6°/km, which is about twice the adiabatic value. Formation of uncommon magma types, such as anorthosites, may perhaps be explained by relatively small and momentary departures from conditions described. Implications of the convection hypothesis on the density distribution in the mantle are briefly discussed.

Introduction--An exact knowledge of the temperature distribution inside the Earth would be of immense value in solving some of the most fundamental problems in the realm of geological sciences. This knowledge would indeed help in determining how magmas form, or to decide between theories of orogenesis by contraction or by convection, or indeed to settle the problem of the origin of the Earth as a cold body or otherwise. Such knowledge, needless to say, is not available, nor is it likely to be forthcoming in the near future. Estimates which have been made at various times by various authors usually merely reproduce the authors' original assumptions as regards the Earth's thermal history or density distribution, or both. "Experimental" determination of the temperature at any depth is theoretically not unfeasible: If we could write two equations expressing the velocities of longitudinal and transverse elastic waves, respectively, as functions of pressure, temperature and composition, these two equations could be solved for temperature and composition given the experimental values of these velocities at all depths, since the pressure distribution is known from independent data. This, however, has not yet been done, although BIRCH [1952] has derived some relations which may be useful in this connection. Birch's derivation is unfortunately limited to a rather special form of the potential-energy function which fits alkali metals rather well, but which finds little support from theoretical or experimental data for more complex structures such as silicates. What we still need is a first-rate theory of solids, particularly of the rigidity of crystalline aggregates as a function of pressure and temperature, plus extremely accurate determinations of their elastic properties and thermal expansions at high temperatures.

The object of the present paper is to review various lines of evidence that may be used to determine minima and maxima temperatures at any depth which would account for some petrological observations.

Minimum temperature in the mantle--The problem of setting a lower limit to the temperature at any depth in the mantle is at first sight a rather simple one. We fortunately have some evidence which bears on the matter, such as the heat flow in continental areas, which is known at least as to its order of magnitude. This, together with an estimate of the radioactive content of continental rocks, makes it possible to calculate the temperature at any shallow depth such as, say, that of the Mohorovicic discontinuity which separates the mantle from the crust. The steady-state temperature at this discontinuity is readily found to lie between 300° and 1000° C, roughly, depending on the exact thickness of the crust (30-50 km?) and on how much of the total heat flow is assumed to be generated in it. The lowest temperature will be obtained, of course, by assuming a thin crust with a high rate of heat generation in it. A crust 50 km thick with an average radioactive content about 50 pct larger than ordinary basalt would generate about 90 pct of the total heat flow, and the steady-state temperature at the discontinuity would be about 775°C. A variation of 100° one way or the other does not make a great difference, and it is suggested, therefore, that we might adopt a figure of about 800° as the steady-state value for this level. This we take to be also a minimum value for the time average at this level, since it appears that the actual temperature at this level occasionally rises well above this value as evidenced, for instance, by local generation of magma.

From this point downward the temperature is not likely to increase at a rate less than the adiabatic gradient, for this gradient represents, among other things, the temperature that would be attained merely by self-compression, neglecting all radiogenic or "original" heat. The adiabatic gradient is unfortunately itself a function of temperature, but various calculations of the ratio of the temperature at any level to the temperature at some predetermined level have been carried out by use of Debye's theory of specific heat and seismic data on the velocity of elastic waves [VERHOOGEN, 1951]. The most recent and more careful calculations are probably those of VALLE [1952] who finds a ratio $T_{2890}/T_{33} = 1.64$. This would give a minimum temperature of about 1500°C at the boundary of the core.

Maximum temperature--It now appears well established that the mantle as a whole behaves as a solid, which means that the temperature at any depth is everywhere less than the melting point at that depth of the lowest melting fraction of the material of which it is made. Knowledge of the change in melting point with pressure for various likely materials will, therefore, set an upper limit to the temperature. This can be done in several ways. The change in melting point with pressure is given by the well-known Clausius-Clapeyron equation

$$dT_m/dP = \Delta V/\Delta S$$

where ΔV is the volume of the liquid minus that of the solid and ΔS is the corresponding difference in entropy. BOWEN and SCHAIRER [1935] have determined this ratio for forsterite and find it to be 4.7°/1000 bars at ordinary pressure; this would put the melting point of forsterite under a pressure of 1.4×10^6 bars, corresponding to the bottom of the mantle, at 8300°C. It is likely, however, that the melting-point coefficient will vary with pressure, and it is easy to see that it will in general decrease with increasing pressure. The reasons for this are first that the compressibility of a liquid is usually considerably larger than that of the corresponding solid; hence the numerator ΔV is bound to decrease with increasing pressure. Secondly, the denominator ΔS may be written as the sum of two terms, the first of which depends on volume and will therefore presumably decrease with increasing pressure like the numerator, while the second term represents a configurational term which is likely to be much less affected, or which may even increase with increasing pressure [SLATER, 1939, pp. 261-265]. That this second term is probably much larger than the first in most silicates that are likely to be of interest may be seen by plotting viscosity of melt against entropy of fusion for various minerals. A high viscosity presumably indicates a high degree of association of molecules in the melt, hence a small configurational change upon melting. SiO_2, with extreme viscosity, has a small entropy of melting (about one entropy unit per mole), whereas diopside, with a large entropy of melting (about seven units per silicon atom) has a viscosity 10^9 times smaller than that of silica glass at the same temperature. This would suggest that roughly 6/7, or 85 pct of the entropy of melting of diopside is configurational, that is, used up in breaking bonds. Similar calculations for olivine and anorthite suggest a similar ratio of the two terms. It is probable, therefore, that the denominator will decrease, if it decreases at all, much more slowly than the numerator, and the slope of the melting curve will become less at higher pressure, in accordance with experimental results at low pressures. The average value of dT_m/dP for olivine in the pressure range involved in the mantle may easily be reduced to 3.5°/1000 bars. The maximum temperature at the core boundary would then be correspondingly reduced to 5700 or 6000°C, possibly even less than that. This maximum figure may also be obtained by a somewhat different method. Partly theoretical and partly empirical considerations lead to the prediction that the melting point of a solid will vary roughly as the square of the velocity of elastic waves in it. If the mantle is chemically homogeneous -- and we shall see that there are reasons to believe that the greatest part of it is homogeneous -- the melting point would be about three times larger at the bottom than at the top. UFFEN [1952] has made some more careful calculations along these lines and concludes that the melting point of olivine at the core boundary is not likely to be much over 5000°C. It is possible, of course, that the dominant constituent of the mantle at that depth is some high-pressure modification with an initial melting point several hundred or even a thousand degrees higher than that of olivine itself. This, however, would probably not change much the melting point at depth, as the high-pressure phase would also have a higher initial elastic velocity.

Petrological evidence--Having thus found that the temperature at the 2900-km level is likely to lie between 1500 and 6000°C, let us see if it could be possible to restrict this range still further. At this point, attention may be called to two important data which may have a bearing on this problem. The first point is based on the well-known fact that lava hardly ever reaches the surface at a temperature higher than 1200°C. Although somewhat higher temperatures have occasionally been observed, they appear to be local and related to reheating by gas combustion and the like; the majority of determinations on lavas from many volcanoes, even in the presence of gas combustion, are consistently less than 1200°C, and study of metamorphism of inclusions in dikes and sills certainly confirms the impression that temperatures as high as 1400 or 1500°C are exceptional, if they occur at all.

To the present writer this must mean that except perhaps under unusual circumstances, of which more later, the temperature at the depth at which remelting and production of magma takes place does not exceed 1200° plus whatever temperature drop corresponds to the heat of melting and subsequent cooling by expansion. These two terms are readily calculated and are found to be relatively unimportant, probably less than 150 or 200° if melting affects not more than 25 pct of the total mass involved, as would be the case if basaltic liquid is produced by partial fusion of meteoritic material. This temperature of about 1400° does not represent the steady-state temperature at the level at which melting occurs; it represents, however, the maximum temperature reached under the circumstances, whatever they are, that lead to local melting and production of basaltic magma.

The other point on which petrological data may have a bearing is that of determining the depth at which this remelting takes place. The evidence on this point is related to what has previously been said concerning the pressure coefficient of the melting point of different minerals. We have already mentioned Bowen and Schairer's value for forsterite: 4.7°/1000 bars. The value for anorthite is of the same order. For diopside it is about 13°/1000 bars, according to YODER [1952], and rough calculation for enstatite and leucite give higher figures of 14 and 16, respectively. For albite the value is 26°/1000 bars, according to GORANSON [1938]. The trend indicated by these figures is that the lower the melting point at ordinary pressure, the higher the value of the coefficient. This means that, at higher pressure, differences in melting temperature become less and less, and melting relationships may eventually become reversed. For instance, Yoder points out that anorthite and albite would melt at the same temperature at a pressure of 22,000 bars; anorthite would presumably melt at a lower temperature than albite at any higher pressure. Similarly, the relationship between olivines and pyroxenes would be reversed at high pressure, and the incongruent melting relationship of enstatite and forsterite might vanish as does that of leucite and orthoclase at relatively small pressures. It is not impossible, therefore, that fractional melting of a basaltic rock at sufficiently high pressure might yield a peridotitic liquid fraction rather than a rhyolitic one; at any rate the composition of the first liquid to form by partial fusion of meteoritic material would change appreciably according to the depth at which this remelting takes place. The very fact that partial fusion of what is commonly thought to be meteoritic material yields a basaltic fraction notably enriched in alkalies and alumina suggests, therefore, that basaltic magmas are produced at a depth at which melting relationships are still normal. From the figure quoted above for reversal in the plagioclase series (22,000 bars), and allowing for gradual flattening of the melting curves, one would infer that production of basaltic liquid must occur at a pressure less than, say, 40,000 or 50,000 bars, correspondingly roughly to a depth of 100-200 km. The maximum height above the ocean floor at which basaltic magma is erupted in the Hawaiian volcanoes, if it represents the effect of density difference between mantle material and liquid melt, suggest a depth of 50 km or so.

A somewhat different situation arises if one accepts Birch's suggestion that the upper mantle, known to seismologists as layer B, consists of eclogitic rather than meteoritic material. In that case, total rather than partial melting would be required to produce a basaltic liquid, and more heat would also be required. Actually, the suggestion of an eclogitic layer does not have much to commend itself to petrologists. Although the density and elastic properties of eclogite fit rather well the upper part of layer B, it should be remembered that eclogite is, on the whole, a rare rock which occurs only in certain associations which strongly suggest a metamorphic origin. Where it is found as inclusions in volcanic rocks, as in kimberlites, it is also associated with other rocks which form a continuous transition to purely metamorphic types such as sillimanite gneisses, granulites, and charnockites. The absence of eclogite as inclusions in basalts of oceanic areas is notable when compared with the frequency of occurrence, in these same basalts, of olivine nodules and fragments of peridotite almost indistinguishable from common peridotites of folded mountain ranges. Peridotite is a common rock as compared with eclogite, and would seem, therefore, to be a more likely constituent of the upper mantle. It should be noted also that the argument that eclogite is a natural suggestion for the mantle because it is, more or less, a high-pressure equivalent of common basalt loses much of its cogency when it is noticed that much the same material which forms layer B under continents apparently reappears also below oceans at very shallow depths where the pressure is not more than 3000 or 4000 bars. As, in addition, experimentally determined values of seismic velocities of dunite and peridotites agree reasonably well with values observed at the top of layer B [BIRCH, SCHAIRER, and SPICER, 1942, p. 80], there seems to be no compelling reason for not assuming that the upper mantle, at least in the zone in which basalt magma forms, is of meteoritic-peridotitic composition.

It may perhaps be appropriate to add here a few remarks concerning the exceptional cases mentioned above. Suppose that partial fusion of meteoritic material occurs at a depth greater than, say, 200 km; then the first liquid to form would not necessarily be richer in the albite or orthoclase molecules than the original solid. It is also conceivable that the effect of pressure on melting in the plagioclase series should not be a linear function of composition; there might become composition intermediate between albite and anorthite, say andesine or labradorite, for which the effect of pressure would be minimum. Partial fusion at the proper depth might therefore lead to separation of a liquid containing an unusually high proportion of this plagioclase and which would be closer to anorthosite than to basalt. It does not appear utterly impossible that magmas of basaltic, or anorthositic or even peridotitic composition could be produced by selective fusion of the same meteoritic material at different depths. This might suggest an explanation for the relatively rare occurrence at certain geologic times of magmas of abnormal composition.

Returning now to the general case of basaltic magma, we find that it is presumably generated by partial fusion of meteoritic material at depths less than 200 km from materials initially at a temperature not higher than about 1400°C. This must surely have some bearing on the problem of determining the maximum temperature in the mantle. Let us draw an adiabatic curve starting from a temperature of 1400° at 100-km depth; the corresponding temperature at the boundary of the core would be, according to Valle's calculations, about 2500°C. This we shall now take to be the highest permissible temperature at that depth. For suppose that the temperature at this level were to exceed this value, being, say 3000°C, while the "normal" temperature at the top of the mantle is about 800°C. Then the average gradient in the mantle would be sufficiently in excess of the adiabatic value for convection to start. The rising material would expand and cool adiabatically. Its temperature at the 100-km level would either be greater than 1400°, which is inconsistent with observations on surface temperature of lavas, or the melting curve of the low-melting fraction would be intersected at a depth greater than 100 km, in which case the magma to form would not be basaltic, which is again inconsistent with petrological observations.

The assumption implicit in this reasoning is, of course, that the gradient required to initiate convection, that is, the adiabatic gradient plus whatever is required to overcome viscosity and fundamental strength is close to (2500 - 800)/2800 = 0.6°/km or, roughly, twice the average adiabatic value. This means that whenever the temperature at the bottom of the mantle exceeds the temperature at 50-km depth by more than 1700° or so, convection will start. The rising material will melt when it reaches approximately the 100-km level to yield a basaltic fraction. If convection starts under a lower gradient or at more shallow depth, the temperature curve of the rising material as a function of its depth may never intersect the melting-point curve; this represents convection without generation of magma. Or, alternatively, if convection only starts under a high gradient, the melting-point curve will be crossed at a depth greater than 100 km, and magmas of aberrant composition may result.

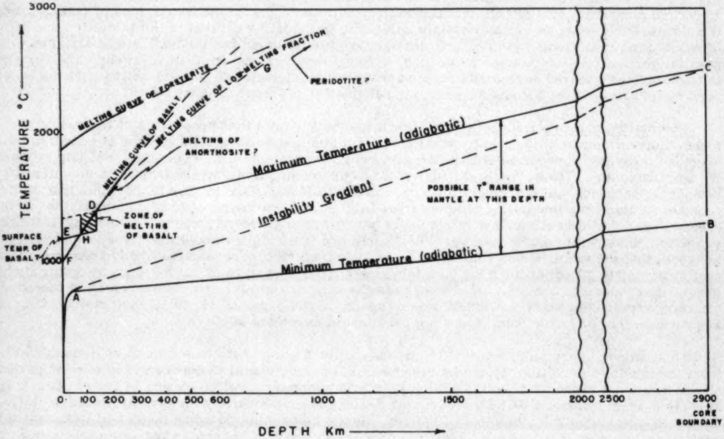

Fig. 28--Relation of temperatures and melting points with respect to depth

This general proposition may be illustrated by referring to Figure 28. The curve OA represents the temperature distribution in the upper 50 km of the crust and mantle in continental areas, assuming that no more than ten per cent of the surface heat flow comes from the mantle itself. AB is the adiabatic curve corresponding to a temperature of 800° at A. The curve FG represents the melting point of the lowest melting portion of meteoritic material; this we take to be at low pressure roughly of the composition of basalt. We accordingly have plotted Yoder's curve for this material, which starts at about 1000° and rises at an initial rate of 10°/1000 bars; but we remember that at higher pressures the composition of the low-melting fraction would gradually change towards a higher proportion of the calcic plagioclase and olivine molecules; at very high pressures this low-melting fraction might consist entirely of olivine. Point E, representing 1200° C, is the maximum surface temperature of basaltic magma; an adiabatic curve from this point (curve E-H) intersects the melting curve FG at point H, and is continued with slight displacement to D. This slight displacement represents the cooling consequent upon adiabatic melting and expansion against an external pressure of 30,000 bars. DC is the adiabatic line through D. The temperature at C is 2500° C. The curve AC represents the "super adiabatic" or instability gradient required to initiate convection. It will be noticed that if we disregard possibility of cooling except by adiabatic expansion (phase change, heat exchange, etc.), the line CD would represent the maximum temperature that could be reached at any depth, consistent with the assumption that no magma will reach the surface at a temperature greater than 1200° C, and that convection can occur throughout the whole thickness of the mantle. The minimum temperature, on the other hand, would be given by a curve such as AB.

One might suggest therefore that the temperature at any depth fluctuates somewhere between these two extreme values, these fluctuations being to some extent time fluctuations, to some extent space fluctuations, as the pattern of convective motion would depend on surface conditions (for example, continental vs. oceanic sectors) as well as on broader features such as the ellipticity of the Earth [VERHOOGEN, 1949]. That such space fluctuations do occur seems to be clearly indicated by recently determined values of the heat flow in the Pacific [REVELLE and MAXWELL, 1952].

On this hypothesis the average temperature at the boundary of the core would be somewhere near 2000°C. This is much less than the temperature (10,000°C) adopted by BULLARD [1948] and ELSASSER [1950] in their calculations of the effect of convection in the core on secular variations of the Earth's magnetic field. It should be noted that, apart from the impossibility of such a high figure, which is inconsistent with all melting-point data, the present value is in better agreement with theory than earlier estimates. Bullard and Elsasser's theories require indeed (1) that the electrical conductivity of the core be as high as possible, and (2) that the thermal conductivity of the core be as low as possible, in order that the very small rate of generation of radioactive heat in the core be sufficient to maintain active convection. Now the ratio of thermal conductivity to electrical conductivity in metals is directly proportional to the temperature, hence, clearly, the temperature has to be as low as possible unless the radioactive content of the metallic core is higher than is reasonable to expect. A low average temperature for the core might also make it possible for the inner core to be solid iron, as suggested long ago by BIRCH [1940]. The very low temperatures suggested here might even warrant reconsideration of the possibility that the inner core be ferromagnetic, accounting thus also for the Earth's main magnetic field.

Possibility of convection in the mantle--It has been shown that production of magma of the right composition and at the right temperature is a straightforward consequence of convectional overturn, provided convection starts under an average gradient of 0.6°/km or so, roughly twice the adiabatic value. This, really, is equivalent to the assumption that the mantle is chemically homogeneous throughout the range in which convection is supposed to take place. In a non-homogeneous medium, the instability gradient (that is, the gradient required to start convection) is increased over the adiabatic value by a term $(1/\rho\alpha)\,(\partial\rho/\partial c)_{PT}\,dc/dh$, where ρ is density, α thermal expansion, h is depth, and c is a variable expressing chemical composition. If we suppose, for instance, that the metal-phase content of the mantle material increases uniformly from zero per cent at the top to 20 pct at the core boundary, the corresponding term in the expression for the instability gradient is 3.5°/km, about ten times the adiabatic value. The temperature at the core boundary required to start convection would then be of the order of 11,000°C, and rising material would reach the top of the mantle at a temperature in excess of 6000°C.

This raises a serious problem. The density ρ_o at the top of the mantle can be determined from the isostatic condition, given the thickness of the continental masses and their average density; it could not exceed 3.5, and the value $\rho_o = 3.32$ adopted by Bullen cannot be far wrong. It is also clear from work of BULLEN [1940] that a homogeneous mantle with uncompressed density 3.3 would have too small a moment of inertia. Hence there must be some degree of inhomogeneity somewhere. Bullen, who uses Jeffreys' data for the velocity of seismic waves as a function of depth (velocity-depth curve), assumes a homogeneous upper layer B, extending down to 413 km depth; changes in composition occur in layer C between 413 and about 900 km. BIRCH [1952] assumes a gradual change in mineralogical composition (phase change) coupled perhaps with changes in gross chemical composition between 200 and 900 km; SHIMAZU [1952] has recently computed a solution with an almost linear increase in the proportion of metallic iron from zero per cent at the top to 20 pct at the bottom. There is no unique solution to the problem, and still other distributions could be found, particularly if one chooses to use different velocity-depth curves, such as those of GUTENBERG [1952] for the upper mantle.

The solution which would least affect the possibility of convection seems to be that of Birch, if the inhomogeneity is assumed to be caused by phase changes rather than by changes in gross chemical composition. A phase change is not necessarily an obstacle to convection, provided the phase transformation occurs on release of pressure in a time that is short in comparison to the rate of motion itself. Birch's solution requires that the phase changes be gradual since there are no first-order discontinuities in Jeffreys' depth-velocity curves, and there seems to be some difficulty in explaining either the nature of the phase transitions involved or why they should be gradual. Birch's argument rests, however, on the application of a density-pressure relation which is not necessarily valid for silicate minerals [VERHOOGEN, 1953], and on the variation with depth of the quantities $\phi = K/\rho$ (K = bulk modulus) and $1 - (1/g)\,(d\phi/dr)$ (g = gravitational acceleration, r distance from the center of the Earth) which seem rather uncertain in the upper mantle, judging by a comparison of Jeffreys' and Gutenberg's values of these quantities (Fig. 29 and 30). The matter apparently requires further consideration.

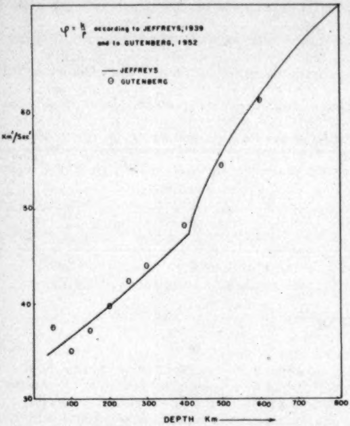

Fig. 29--Variation of velocity with depth

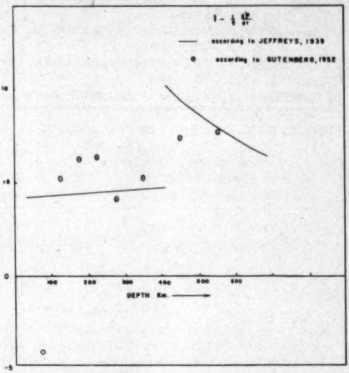

Fig. 30--Variation of 1 - (1/g) (dϕ/dr) with depth

Conclusion--Summarizing, the purpose of this paper is to show that if the mantle is sufficiently homogeneous between a depth of 150 km and the core boundary to allow convection under an initial gradient of 0.6°/km, the maximum temperature at the boundary of the core cannot exceed 2500° and probably fluctuates, in time and space, between this value and a minimum value of about 1500°. Production of magma of the right composition and at the right temperature follows automatically from these premises. If inhomogeneity in the mantle, or part of it, raises the instability gradient above this limit, production of magma cannot be understood as a result of wholesale convection. Although some magma could still be produced as a result of limited convection in the shallow zone above that in which chemical inhomogeneity occurs, the only known upper limit to the temperature of the core is then that obtained from Uffen's calculation on the change in melting point with pressure, namely, 5000-6000° C.

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DISCUSSION

Harvey Brooks (Cruft Laboratory, Harvard University, Cambridge 38, Mass.)--The convective theory presupposes the simultaneous existence of a superadiabatic vertical temperature gradient in the mantle and a horizontal temperature contrast sufficient to overcome the fundamental strength of the mantle and cause it to yield plastically. A vertical gradient alone is insufficient since, although unstable, it produces no stresses. A horizontal contrast can produce enough stresses to initiate flow, but the transport of heat resulting from the flow will decrease the horizontal contrast, and hence the stress, unless an unstable vertical gradient is present. Thus in a plastic mantle it is difficult to see how a convective theory can be applicable unless the existence of a temperature difference between core and crust greater than adiabatic is established before the horizontal contrast is sufficient to start flow.

With the above considerations in mind, the convection theory encounters a rather major difficulty. It is that the time required for re-establishment of an unstable gradient by conduction after a convective overturn is nearly ten times the age of the Earth. From this it would appear that in any given geographical region, a convection cycle could occur once and only once in the Earth's history. The time for re-establishment of the vertical temperature distribution is given in order of magnitude by

$$t = \rho c h^2 / 4\pi^2 k$$

Taking $k/\rho c$ = thermal diffusivity = 0.01, h = 3000 km, we obtain $t = 2.5 \times 10^{10}$ years. The discrepancy is much too large to be affected by details of the assumptions used in making the calculation.

A second difficulty is posed in the picture given us by Verhoogen. The temperature relations pictured by him are shown schematically in the accompanying diagram:

-275°	+325°
+125	-125
+525	-575

In this diagram we have indicated "potential" temperature rather than actual temperature, and we have chosen an arbitrary zero to bring out the symmetry of the problem. The "potential" temperature is simply the temperature which a given sample of the mantle would reach if compressed adiabatically to a standard volume.

It is seen from the diagram that the mean superadiabatic gradient is very small. In fact, within the framework of the reasoning used by Verhoogen, it could be of either sign, but if anything it is stable. If we consider the whole region to be divided into six blocks of equal volume, each isothermal, as indicated in the diagram, then it is seen that if each block advances one step in the convection cycle the contrast in average temperature between the two vertical columns drops from 250° in favor of the left column to only 67° in favor of the left column. Thus the situation represented in the schematic diagram is actually stable in the sense that the initiation of the cycle results in a reduction of the driving forces.

The contrasting gradients postulated by Verhoogen are much more effective in producing thermal perturbations which favor two layers of convection cells rather than a single large cell. Such a perturbation is less effective in overcoming the fundamental strength. Thus it may be said that Verhoogen's temperature distribution is not especially favorable for overcoming the fundamental strength of the mantle.

Verhoogen's deduction of a small core temperature from the observed temperature of lava is not entirely convincing from the standpoint of the convection picture. Due to the time scale involved the heat transport in a convective overturn is entirely by motion. Since the velocity is negligible in the vicinity of the crust, the heated material is not raised all the way to the surface of the mantle but only to a depth within a few hundred kilometers of the surface. Since the lavas probably originate at a depth of less than 100 km in the mantle, it is probable that they have their origin in a region whose temperature has been influenced to only a minor degree by transport of heated material up from the core boundary. Thus it is not legitimate to use the lava temperature to set an upper limit to the temperature at the core boundary.

Finally it must be recognized that Birch's evidence for the existence of a structure in the mantle is an additional difficulty in the convection hypothesis. This difficulty is perhaps not fatal, however. In the first place there is the possibility of a reversible phase change at 900 km through which the convection can occur without significant modification of the stratification. If there is appreciable latent heat in this transformation, it may contribute significantly to triggering the convection cycle. Indeed if the latent-heat and volume-change relations are correct, a superadiabatic gradient would not be necessary to produce convective instability. This could be produced by the phase transformation alone. Furthermore, unstable conditions could be re-established by conduction over a much smaller vertical height than in the case of a superadiabatic gradient in a uniform mantle. Thus the existence of a reversible phase change might overcome the difficulty regarding excessive times for re-establishment of instability.

The homogeneous region of the mantle is still 2000 km thick, and could easily support a convection cycle within itself. It is then possible that the tractions exercised by this large cell on the 900-km layer near the surface would be sufficient to produce a forced convection in this layer, which would in turn generate the mountain-building forces on the crust. If the density discontinuity is large enough, and the layer is isothermal, breakthrough from the lower region of the mantle may not occur. If this represents the actual situation, it removes one of Verhoogen's arguments for the relatively low temperature of the core boundary, for now the material at the depth from which lavas originate has not been transported up from the core boundary, and therefore does not have to have the potential temperature of this boundary. The difficulty of re-establishment of the vertical gradient within the lower layer still remains in this picture, however, and the mountain-building forces at the crust will be substantially reduced. No detailed calculations have been made on this model.

The writer would like to acknowledge the benefit of several conversations with Francis Birch.

David Griggs (Institute of Geophysics, University of California, Los Angeles 24, Calif.)--I am happy to have this opportunity to express publicly my appreciation of the service that BIRCH [1952] has rendered to the science of geophysics by publication of his excellent paper entitled The Elasticity and Constitution of the Earth's Interior. This paper contains a wealth of data and techniques indispensable to anyone interested in furthering our quantitative knowledge of the interior of the Earth. Birch's paper on the same subject in this Symposium has added importantly to his earlier work.

With regard to one of Birch's central conclusions: that the mantle from 200 to 900 km depth is inhomogeneous, I am forced to agree with Verhoogen that the data, both experimental and seismic, is insufficient to support such a conclusion, though I must admit that Birch's conclusion is a plausible one. Birch's argument rests on the somewhat erratic variation in $(\partial K_T/\partial P)_T$ deduced from seismic velocities in the 200-900 km depth as contrasted to a slowly decreasing variation to be expected from his adaptation of Murnaghan's theory of finite strain. In this argument Birch expresses the Helmholtz free energy ψ in the form

$$\psi = af^2 + bf^3 + cf^4 + \dots$$

where f is the hydrostatic strain, taken to be positive for compression. He shows that for Bridgman's data on the most compressible elements (the alkali metals) $b/a = 0 \pm 0.1$, and terms higher than b vanish. This allows him to derive a simple one-parameter equation

$$(\partial K_T/\partial P)_T = (12 + 49f)/3\,(1 + 7f)$$

which is then presumed to apply to the mantle of the Earth, since the maximum compressions in the mantle are less than those already obtained by Bridgman in the alkali metals.

VERHOOGEN [1953] has adduced plausible arguments that the free energy of the silicates would not follow such a simple relationship. Unfortunately, this point cannot yet be adequately tested by the experimental data. Quartz is the only silicate which Bridgman has measured to 100,000 bars ($\simeq$300 km). $(\Delta K_T/\Delta P)_T$ derived from these data shows a variation over this pressure range similar to that derived from the seismic velocities in the Earth. Unhappily, however, it appears that Bridgman's data on quartz is internally inconsistent. For what it is worth, a least-squares fit of Bridgman's data gives $b/a = 7.6$, and hence, $(\partial K_T/\partial P)_T$ about double that for $b/a = 0$.

I have calculated the function $1 = (1/g)\,\Delta\phi/\Delta r$ from seismic data other than those used by Birch (for example, Gutenberg and Richter, 1939) and find, as did Birch and Verhoogen, that the deduced $(\partial K_T/\partial P)_T$ is quite sensitive to what data are used.

The basic trouble is that such analyses depend on the second derivative of compression measurements and on differences of the squares of seismic velocities. An accuracy which is an order of magnitude higher is required for both experimental and seismic measurements in order to test Birch's hypothesis adequately. It is to be hoped that Birch's argument will provide additional incentive to achieve these higher accuracies.

Turning to Verhoogen's paper of this Symposium, his speculation that mantle temperatures depend on deep-seated convection and that this in turn can lead to the formation of near-surface magmas is very provocative. One attractive feature of this hypothesis is that it would provide a satisfactory primary mechanism for the continual growth of continents and oceans by means of selective fusion, for which Rubey has adduced compelling arguments.

With respect to Brooks' point, raised in the preceding discussion, that the time-constant for re-establishment of an unstable gradient after a convective overturn would be long compared to the age of the Earth, and that hence a maximum of one overturn could have occurred in any one region, BROOKS [1941] pointed out, "On the other hand, it is probable that the flow is of the pseudo-viscous type exhibited by stressed solids under laboratory conditions, in which the viscosity decreases rapidly with the applied stress. It is not possible to give a rigorous solution of the convection equations in the case of pseudo-viscous flow, but we have obtained an approximate result for one case, which gives a good idea at least of the direction in which the results should be modified. One finds that the motion is relatively more concentrated towards the outer edge of the cell than in ordinary flow and that, therefore, the hot and cold strata shown in the diagram will be relatively much thinner, and will hence lose their temperature-difference much more rapidly than we have calculated." I hope that Brooks, who is pre-eminently qualified for the job, will continue his active interest in this problem, and be able to obtain a more definite picture of what form convection in the mantle would take. Only then can one say what are the appropriate time constants, velocities, and shear stresses.

I would like to take this opportunity to mention two related developments: (1) the consequences of the heat flow measured in the Pacific; (2) the implications of continued formation of the ocean and crust for tectonic processes. The two recent expeditions by Scripps Institution have made measurements of heat flow through the floor of the Pacific over a considerable area. The heat flow is found to be 1.2 microcal cm^{-2} sec^{-1}, about the same as that through the continental surface. Because of the measured concentration of radioactive elements in continental rocks, it is presumed that about three-fourths of the continental heat flow has its origin in the crust itself. Seismic measurements by Scripps under the Pacific show about two km of unconsolidated sediment underlain by a crust about five km thick with seismic characteristics usually associated with "basalt." These would be expected to contribute something less than 0.2 microcal cm^{-2} sec^{-1} to the heat flow. Hence the heat flow through the Mohorovicic discontinuity would be about three times larger under the oceans than under the continents. As REVELLE and MAXWELL [1952] have pointed out, the consequent temperature gradient is such as to preclude a mantle in thermal equilibrium, which lead them to suggest convection under the Pacific as an explanation.

In order that the temperature not rise above the melting point for thermal equilibrium of the mantle under the Pacific, it is necessary that most of the radioactivity be concentrated in the upper part of the mantle. Specifically, I calculate, using conventional assumptions as to conductivity, etc. [BIRCH, 1950, p. 619, Model C] that if enough radioactivity to account for 0.7 microcal cm^{-2} sec^{-1} were distributed uniformly in the outer 100 km of the mantle, the temperature at the bottom of this layer (depth 111 km) would be 1500°C. Verhoogen (above) has estimated the melting temperature at this depth to be about 1400°C. Hence most of the radioactivity must be concentrated in the outer 100 km or less of the mantle for a model in thermal equilibrium. The corresponding average radioactivity content of this layer would be equal to or greater than 0.7×10^{-13} cal cm^{-3} sec^{-1}, 20 times that normally associated with the outer mantle, and comparable to that in continental basalts. Such an improbable distribution of radioactivity would have serious consequences in terms of isostatic balance of continental and oceanic segments due to temperature differences in the mantle. The temperature under Birch's "normal continent" at a depth of 111 km would be about 600°C; hundreds of degrees cooler than at a similar level under the oceans. This would cause a negative gravity anomaly of some hundreds of milligals over the Pacific, whereas the observed average anomaly is about + 10 milligals.

One is thus forced to postulate: (1) nearly identical distribution of radioactivity with depth in continental and oceanic sectors which seems unreasonable; (2) a variation of the intrinsic density of the mantle from continental to oceanic sectors in such a way as to balance precisely the thermal expansion; or (3) a non-equilibrium model; hence mass transport of hot mantle material to a position under the Pacific.

Of the three alternatives, only the last seems acceptable to me. Further, of the various types of mass transport that one can think of, only convective overturn could readily account for the exact match of average density of the mantle in the two sectors which is required by the observed isostatic balance of continents and oceans. I thus find myself in agreement with Revelle and Maxwell.

Next, we turn to the tectonic implications of continued formation of oceans and continents. RUBEY [1951] has presented compelling arguments that the water of the oceans and the rocks of the continents have been extracted from the mantle at a roughly constant rate throughout geologic time. It is clear that such processes would have important tectonic effects. RUBEY [1953] has explored this subject in a thorough and most interesting fashion. I commend his paper to your attention when it is published.

I shall deal with two aspects of this problem that have not been covered by Rubey. First, the hypothesis of autocatalytic formation of continents and ocean basins. We assume, following Rubey, that the mantle is locally brought to a temperature and pressure such that its lowest melting constituents will melt (this can be done by either radioactive heating or convection as Verhoogen has suggested); that in the course of time a part of this melt will separate from the unmelted residuum of the mantle; and that this separated fraction will later crystallize into a more acidic and lighter rock which forms an increment to the crust. Incidentally, Rubey has calculated that 15 parts of mantle would have to be so "selectively fused" to create one part of continental crust.

Let us suppose that there is selective fusion of the radioactive material and concentration in the crust concomitant with the above process. It then follows that where the crust is thicker the temperature at the base of the crust will be higher. Hence, cooling of any selectively fused mantle under such a region will be slower than under a thinner, less radioactive crust, and the process of selective fusion will therefore proceed more slowly. In addition, it would seem that selectively fused mantle could rise closer to the surface under a thinner crust and hence lose heat more rapidly for this reason as well. Now it is only necessary to postulate that the separation of the selectively fused material is time dependent, and that continued selective fusion is randomly spaced over the globe and repeated at short time intervals. We now have an autocatalytic continent-forming mechanism.

The degree of fractionation and also the amount of selectively fused material separated will be greater where the pre-existing crust is thicker. We have thus an unstable situation in which continents will tend to grow at a faster rate than the thin sub-oceanic crust. This process could in principle account for the origin of continents and ocean basins, if the initial conditions of selective fusion and the time constant of repetitive events were proper.

Next we turn to another aspect of Rubey's theory of crustal growth by selective fusion: a possible mountain-building mechanism. Let us suppose that a linear element of the mantle, say 100 km wide and 50 km deep, has been selectively fused immediately below the crust, and that one-fifteenth of its volume has been separated and crystallized into crustal rock. Rubey has calculated that the unmelted residuum, from which this material has separated, will have a density one per cent greater than the unseparated mantle at the same temperature and pressure (if it were 500°C hotter than the unmelted mantle, it would still have a density 0.5 pct greater). Such a density difference would cause the unmelted residual block to sink in the surrounding mantle. With a mantle of viscosity of 10^{22} poises, its steady-state velocity of sinking would be of the order of five km per million years.

As the sinking block is separating from the crust, and while it still remains relatively close to the crust, the inflow of surrounding mantle material to replace the volume formerly occupied by the sinking block will exert a substantial viscous drag on the crust, toward the center of the position formerly occupied by the block. I estimate that this viscous drag can exert a shear stress on the bottom of the crust of the order of 1000 kg/cm^2. The duration of this force would be a few million years. Such a force is sufficient to be of importance in mountain building.

An important corollary to this which Rubey has pointed out is that the crust under which selective fusion and recrystallization is taking place will be subject to large isostatic changes of level. The crust will first rise as the subjacent block is partially melted. It will then sink as the separated melted fraction crystallizes, and finally, when the unmelted residual block sinks in the substratum, the crust will rise again. I estimate these changes to be respectively +1 km, - 0.5 km, + 2 km. Such changes could be important in epeirogenesis and in geosynclinal formation. The above figures apply to the surface of an unmodified crust. Erosion or deposition could amplify these changes as measured on a geologic stratum.

Another corollary to the sinking of the unmelted residual block is that hot mantle below the block will be displaced upward. Since we have reason to believe that the temperature gradient immediately under the mantle is greatly in excess of the adiabatic gradient, this material could thus be brought above its melting point and in turn partially fused. Each successive displaced volume would be melted less than its predecessor, however, so that this would only prolong the process, and would not initiate it or keep it going indefinitely.

Finally, it should be pointed out that while convection and magma formation as suggested by Verhoogen is not essential to these hypotheses of autocatalytic continent formation and mountain building by drag from the sinking block, it would be a convenient primary mechanism for these and for Rubey's hypothesis crustal growth by selective fusion.

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J. Verhoogen (Department of Geological Sciences, University of California, Berkeley 4, Calif.) --Brooks has presented several objections to my method of setting an upper limit to the temperature of the core from the surface temperature of lavas. He points out in the first place that the hottest material rising from the core boundary would never reach the 100-km level; the temperature distribution after a convective overturn would show a maximum at about 600-km depth, and the temperature at the 100-km level could not be taken to indicate the temperature initially prevailing at the core boundary.

While this may be true, it does not appear to affect our conclusions very seriously. In the first place, the depth at which the temperature would be maximum after the overturn depends on the total thickness of the convection cell. Brooks goes on to show that under the conditions postulated by the writer the circulation would tend to break up into two sub-cells extending halfway down the mantle; this would probably considerably reduce the depth at which the maximum temperature would occur. Yet let us assume that this depth is 600 km; reference to Figure 28 shows that the melting point at this depth is just over 2000°C. Now melting presumably does not occur at that depth, as it would produce non-basaltic magmas which would reach the surface at a temperature greater than 1200°C; hence the maximum temperature at that depth after the overturn is less than 2000°C, and the maximum initial temperature at the core boundary cannot be much greater than 2800°C, the ratio of the (absolute) temperatures T_{2900}/T_{600} being 1.34 for adiabatic expansion, according to Valle. This increases our previous estimate by 300° only.

The matter of the time constant for convectional overturn is difficult to discuss adequately. Brooks [see also BROOKS, 1941] has pointed out that the temperature distribution at the end of a convection cycle would decay by conduction exponentially with a mean life of several billion years; this would make a convective overturn a rare event indeed. These theoretical calculations, however, make no allowance for the (unknown) rate at which heat is supplied from the core boundary, or for (unknown) variation with depth of rate of heat generation in the mantle itself, or for the cooling in the upper levels that may be due to production of magma or to phase transformations. It is also difficult to estimate the actual volume of material taking part in the motion. Clearly, if basaltic magma is to be produced in the manner postulated here, the volume of circulating material, or rather the volume of material crossing the level at which remelting takes place, cannot be very large since roughly 25 pct of this material would melt and about ten per cent of the liquid would reach the surface (assuming that it rises to the surface mainly because of expansion upon melting). The total amount of basaltic material erupted since the end of the Precambrian is probably less than 10^{23} cm^3; the total amount of material that has crossed the melting level since that time would thus be less than 4×10^{24} cm^3, which is a small fraction of the volume of the mantle. A single current rising at an average rate of 1 cm/year over an area one-hundredth of the Earth's surface would deliver in the same time about six times that amount. This suggests that active circulation may be restricted to narrow zones within the convection cells, as BROOKS [1941] has found would be the case if viscosity depends on the applied stresses. The time constant in such cases could, as Brooks points out, be appreciably shorter.

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B. Gutenberg (Seismological Laboratory, California Institute of Technology, Pasadena, Calif.) --There seem to be at least two levels in the Earth's mantle at which rather rapid changes take place. The first is at a depth of about 700 km. There, the number as well as the energy of deep-focus earthquakes decrease very rapidly. At present no deep-focus earthquakes are known below about 720 km. Roughly at the same depth electric conductivity has been found to increase rapidly. Whether or not there is a direct or indirect connection between these two phenomena is not known.

The second change occurs at a depth of about 950 km. Wiechert has been the first to recognize that at an epicentral distance of about 43° the slope of the travel-time curve for direct longitudinal waves changes appreciably. This has been confirmed later repeatedly by others and there is also a corresponding decrease in amplitudes near that epicentral distance. All determinations of depth at which the longitudinal waves emerging at 43° have their deepest point have led to values in excess of 900 km, some even below 1000 km. The depth interval of at least 200 km between the two levels is too great to refer them to one and the same discontinuity.

Francis Birch (Harvard University, Cambridge 38, Mass.)--Let me remind you again that the conclusion that the mantle is not homogeneous in both phase and composition does not depend upon a particular equation of state, but, as explained above, upon the assumptions that (1) the seismic velocities are approximately correct, (2) the ratio I/MR^2 for the core cannot exceed 0.4, and (3) the density at the top of the mantle is less than 3.7. If these very plausible assumptions are accepted, then we must conclude that the mantle departs from homogeneity, and the next question is to find where it does so and why. The analysis employing an equation of state is directed to this second objective, not to the basic question of homogeneity which has already been decided by Bullen's method.

It now appears likely that the flow of heat to the surface is about the same in continents and oceans; following Bullard, we may explain this by supposing that the total radioactive content per unit of surface is everywhere roughly the same. But the relatively high concentration of radioactivity in typically continental rocks is, at least qualitatively, one of the best-established geochemical facts. Thus we are led to the conclusion that the radioactive content of the suboceanic rocks is greater than that of the rocks below the Mohorovicic discontinuity below the continents. Such a horizontal difference is inconsistent with the movements of material postulated by convectionists. Alternatively, if convection is invoked to account for the oceanic heat flow, then the rough equality with continental heat flow and the absence of thermal anomalies on a scale corresponding with cell dimensions require further explanation. The measurements of heat flow at sea, as they now stand, seem to me to constitute our most definite evidence against convection currents affecting the shallow levels of the mantle.

Clarence S. Ross (U. S. Geological Survey, Washington 25, D. C.)--Some recent work in the laboratories of the U. S. Geological Survey may be significant in connection with the remarks of Birch. Many geologists have believed that dunites represent material derived from the peridotite zone of the Earth's crust. Similar olivine-rich materials have a world-wide occurrence as nodular inclusions in basaltic rocks. These have in general been considered to represent segregations from the basaltic rocks. However, intensive studies of these inclusions indicate that they too are derived from the peridotite zone, having been dragged up from profound depths. Thus, we have two distinct mechanisms which seem to have sampled the peridotite zone. It is significant that the minerals and the mineral compositions are essentially identical in the materials resulting from these different mechanisms. The minerals occurring in both dunites and inclusions in basaltic rocks are olivine (dominant), enstatite, chromian diopside, and chrome rich spinels or chromite.

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RESULTS OBTAINED BY THE FINNISH SOLAR ECLIPSE EXPEDITIONS, 1947

T. J. Kukkamäki

Abstract--In 1947, the Finnish Geodetic Institute sent two expeditions to observe the total solar eclipse; one to Brazil, the other to the Gold Coast. The purpose of the expeditions was to determine the distance between the observation points through observation of the moments when the shadow of the Moon passes the observation points. These expeditions used specially constructed cameras which had been designed for solar eclipse recordings and featured a smoothly moving film (as contrasted to the jerky movement of film in commercial camera). Both expeditions were successful. The evaluation of their films gave the distance between two observation places with an accuracy of ± 94 m. This error was mainly due to the prevailing poor knowledge of the profile of the Moon. When better values for the profile are available, it is expected that the error will be reduced to about half its present size.

Introduction--By timing solar-eclipse contacts along the central line of the eclipse, it is possible to determine the distances between observation points. This is of great importance in geodesy, as it enables us to measure distances across oceans, which would be impossible with terrestrial triangulation methods.

The solar-eclipse idea has been known for a long time, but visual observation of the contacts has not been accurate enough for results comparable to those obtained by geodetic methods. Modern radio and motion-picture techniques afford great possibilities for increasing the accuracy of the solar-eclipse method. The first attempt at using such techniques was made by the Polish scientist, Th. Banachiewicz, in 1927. In 1945, on the initiative of the late I. Bonsdorff, Director of the Finnish Geodetic Institute, Finnish and Swedish expeditions were formed which used sound film cameras for taking pictures of the solar eclipse while recording radio time signals on the same film. The positive results of these efforts encouraged the building of a new type of camera for the eclipse of May 20, 1947, which was very suitable for geodetic purposes. Five special cameras were built; one for Argentina, two for Sweden, and two for two Finnish expeditions, one of which went to Brazil under R. A. Hirvonen's supervision and the other to the Gold Coast in British West Africa under my supervision.

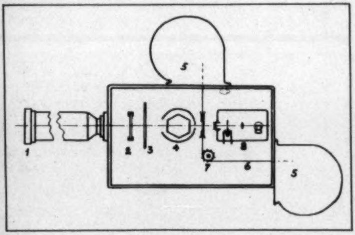

Fig. 1--Schematic picture of the camera

Instrumentation--The special camera (see Fig. 1) uses ordinary 35-mm film. It differs from the ordinary sound-film camera mainly because its film does not move jerkily. The cog wheel (7) moves the film at an even speed of 24 pictures per second. Light comes through the 206-cm focal-length objective (1), through a color filter (2), a front shutter (3), a drum shutter and a glass prism (4) onto the film in the picture-window canal. If two of the prism surfaces are in vertical position, the image appears in the middle of the picture window. When the prism rotates in a clockwise direction, the image moves downward until the subsequent pair of prism surfaces comes into the path of the light. At this point the image jumps up and again moves downward. By proper dimensions of the prism it has been possible to have the image follow the film with an accuracy of one micron. The radio signals and the ticks of a clock are projected onto the film by a pair of oscillators (8); one type of signal on each border of the film, and outside the holes. In Figure 2 a reproduction of the film is given. In the central area of this film the images of the crescent of the Sun can be seen. The chronometer ticks are recorded on the left border of the film and the radio signals on the right border.

Observations--The aim of both Finnish expeditions was to photograph the disappearance and appearance of the Sun's crescent for a period of 30 seconds at the second and third contacts. Both

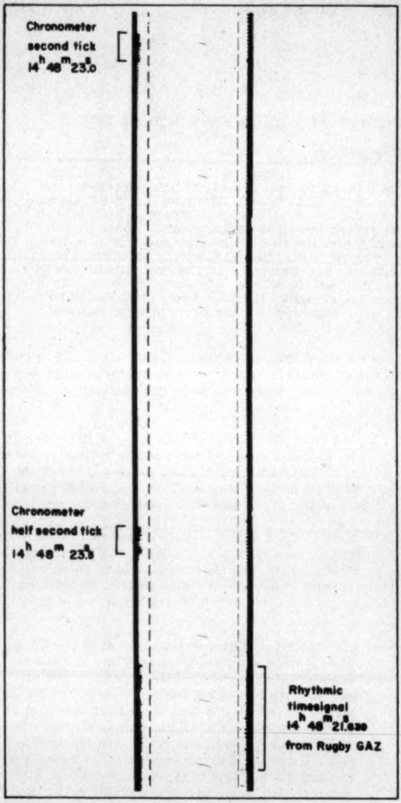

Fig. 2--The crescent of the Sun eight seconds before the second contact of the eclipse in the Gold Coast

expeditions were successful, except for some technical trouble in Brazil which caused the photographic process to be interrupted for ten seconds before the second contact.

In Africa the Rugby signals were used for timing and the exposure moments were read from the film with an accuracy of 0.003 sec. In Brazil the Buenos Aires LOL signal and the ticks of chronometers compared with the Rugby GBR signals were used and an accuracy of 0.01 sec was attained.

Because slight periodic deviations in the positions of the pictures on the film were found due to the asymmetry of the six-sided prism, every sixth picture on the film was measured. The measurement of the intervening pictures would not essentially increase the accuracy because the Moon's topography is the most important source of error and the cusp of the Sun's crescent moves rather little in the course of the six pictures. From the Brazilian film 59 pictures of the second contact, and 84 pictures of the third contact have been analyzed. From the Gold Coast film 93 pictures of the second contact and 61 pictures of the third contact were analyzed. From each picture the coordinates of the end points of the crescent or, if possible, of Bailey's beads, were measured with a microscope. These coordinates (see Fig. 3) give the selenographic position angles counted from the north pole of the Moon. These angles are reduced to the value $930''.0$ of the radius of the Moon by the aid of the Moon's profile map by HAYN [1902, 1904, 1907, 1914]. When we add the position angle C of the Moon's north pole, counted from the north, to the mean of the position angles of the north and south end of the crescent $\pi_T = (\pi_N + \pi_S)/2$ we get the direction angle $M = \pi_T + C$.

The angle M gives on the fundamental plane (see Fig. 4) the direction of the Moon-Sun axis (x, y) from the observation point (ξ, η).

The distance m from the Moon-Sun axis to the observation point can be calculated from

$$\tan^2 B/2 = (L_1 - m)(m + L_2)/(L_1 + m)(m - L_2)$$

which can be found in astronomy text books. The angle $B = \pi_{NS} - \pi_T$ is calculated and using the notation $\beta = \tan^2 B/2$ we get

$$m = (1/2)\,[(1-\beta)/(1+\beta)]\,(L_1 - L_2) - \sqrt{(1/4)\,[(1-\beta)/(1+\beta)]^2\,(L_1 - L_2)^2 + L_1 L_2}$$

Thus we calculated from the film data the distance m_{obs} and its direction angle M_{obs} corresponding to the exposure moment of each picture.

On the other hand, from preliminary coordinates for the observation points we can also calculate m and M. The comparison of the observed and calculated values of M and m gives corrections to the preliminary coordinates of the observation points.

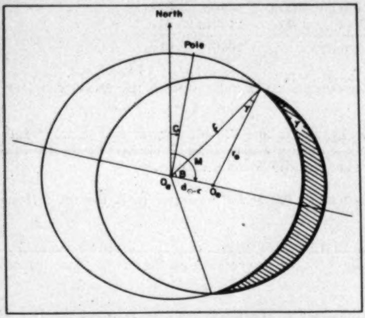

Fig. 3--The apparent positions ($0_{\odot}$, $0_{\text{☾}}$) of the Sun and the Moon; L_1 = radius of penumbra; L_2 = radius of umbra at the observation point; $r_{\odot} = [(L_1 + L_2)/(L_1 + L_2)]\, r_{\odot}$; $r_{\text{☾}} = [(L_1 - L_2)/(L_1 + L_2)]\, r_{\odot}$, $d_{\odot-\text{☾}} = [2m/(L_1 + L_2)]\, r_{\odot}$

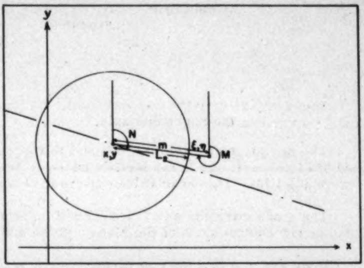

Fig. 4--The distance and the direction of the Moon-Sun axis (x, y) from the observation point (ξ, η) on the fundamental plane

The preliminary coordinates of the Brazilian station based on the astronomical observations of the American Solar Eclipse Expedition are

$$\phi = -17^{\circ}\,14'\,01''.88 \qquad \lambda = +43^{\circ}\,40'\,15''.20 \qquad h = 789\text{m}$$

The coordinates of the Gold Coast station are tied to the first-class triangulation comprising ten astronomically determined points and are

$$\phi = +6^{\circ}\,09'\,56''.34 \qquad \lambda = -0^{\circ}\,01'\,01''.02 \qquad h = 221.0\text{ m}$$

For the calculation of M and m the Besselian elements computed with seven digits by HIRVONEN were used.

At first the correction perpendicular to the central line of the eclipse has to be considered. For the direction angle M the predicted and observed values shown in Table 1 were obtained.

Table 1--Predicted and observed values of M

Location	Contact	M_{pred}	M_{obs}	ϵ_{prob}
Brazil	Second	235°.82	235°.95	±0°.13
	Third	55 .79	58 .05	±0 .55
Gold Coast	Second	251 .60	251 .64	±0 .07
	Third	71 .28	71 .59	±0 .37

The error in the third contact is due to the poorer profile of the corresponding part of the Moon's limb and to the greater refraction disturbances after the eclipse than before it. Owing to this fact we use the M_{obs} value from the second contact only. From the differences ($M_{pred} - M_{obs}$) we calculate the deviation of the observation point from the preliminary position normal in the vertical direction to the central line of the eclipse. They are: in Brazil, 240 ± 240 m in azimuth 146°; in the Gold Coast, 70± 117 in azimuth 161°.

Secondly, the correction along the central line of the eclipse has to be considered. This gives the correction to the distance between the observation points. For the exposure moment of each picture the value m_{pred} is calculated and then the corresponding observed value m_{obs}. The difference between these values gives the correction to the position of the observation points in the direction of the eclipse's central line. The weighted means of the corrections are

Brazil

In azimuth 236°	Second contact	2140m ± 105m
	Third contact	1410m ± 95m
	mean	1775m ± 71m

Gold Coast			
	In azimuth	Second contact	1880m ± 82m
	251°	Third contact	1400m ± 91m
		mean	1640m ± 61m

These values give the corrections in the fundamental plane which contains the Earth's center and is normal to the Sun-Moon axis.

The deviations between second and third contacts, 730 m and 480 m, correspond to only 0"20 and 0"13 respectively in the Moon's radius. An error of this amount can be caused by the irradiation of the film. The mean values are free of the error in the Moon's radius.

The mean corrections 1775 and 1640 m correspond to 1"0 and 0"9 respectively for the difference of right ascensions of the Moon and the Sun.

If we assume that the coordinates of one of the stations are correct, then the correction for the other station is the difference, or 135± 94 m, which is the correction on the fundamental plane in the direction of the central line.

This correction converted from the fundamental plane to the Earth's surface is for the Brazilian station, keeping the Gold Coast station fixed: dϕ, -4"2 ± 2"9; dλ, +5"4 ± 3"7; and in azimuth 231°, 206 ± 143 m; and for the Gold Coast station keeping the Brazilian station fixed: dϕ, +0°.1 ±0°.0; dλ, -5°.8 ± 4°.0; and in azimuth 89°, 177 ± 123 m.

The most important source of error lies in the Moon's profile which is considered here by the aid of Hayn's map. The accuracy of this map is not very high. At present, Watts of the U. S. Naval Observatory is preparing a new map which is expected to give double the accuracy. If this is possible, the errors in the fundamental plane which now exceed 60 - 70 m can be reduced at least by half, that is, to 30 - 40 m.

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EFFECTS OF THE COSMIC RADIATION ON TERRESTRIAL ISOTOPE DISTRIBUTION

Serge A. Korff

Abstract--The effects of the cosmic radiation in building up and altering the terrestrial isotope distribution are computed. The most striking effect is the production of radiocarbon, but as this beta-decays to nitrogen it does not alter the distribution permanently. The second important process is the production of tritium, and its subsequent decay into helium three. The problem is discussed quantitatively. Finally it is shown that several other possible reactions do not contribute in an important degree to the existing distribution.

Introduction

It is well known that the Earth is subject to a radiation having sufficient energy to produce nuclear transformations, and it is pertinent to ask whether quantitive calculations can now be made as to the effects of this radiation on the distribution of isotopes. In this paper we shall endeavor to estimate the amounts of several processes now operative.

The primary cosmic radiation comprises, by number, approximately 90 pct protons, some nine per cent of alpha particles, and about one per cent of heavier nuclei, the number decreasing as the atomic number Z of the particle increases. These incoming particles have energies between 2 and 100×10^9 electron volts, though a few have energies much higher, perhaps up to 10^{14} or 10^{16} ev. The incident flux is known to be around $0.34/\mathrm{cm}^2$ sec reaching the top of the atmosphere. In this paper we are not concerned with latitude effect, and consider only integrated totals over the entire Earth.

Effects of the radiation--The radiation just described, when incident upon atoms in the atmosphere, produces a secondary radiation, which contains all known kinds of atomic fragments and other entities. In this paper we are not concerned with mesons, photons, or electrons, but shall merely consider the nucleons. The primary nucleons produce secondary nucleons, and these often have enough energy to produce still further nuclear disintegrations. The total process is called a "nuclear cascade." The low-energy disintegrations are the well-known "nuclear evaporation" stars seen in photographic emulsions. These secondary processes are the main source of the neutrons associated with the cosmic radiation. The rates of neutron production have been measured and are known, both as totals and at various altitudes and latitudes. The neutrons are the main agents active in building up new isotopes, although the charged particles also have enough energy to do so. The charged particles, both in the primary and secondary radiation, lose most of their energy in scattering, meson-production, ionization, radiation, and disruption processes; they contribute comparatively little to isotope formation. The neutrons, however, are all eventually absorbed by nuclei and thus do build up isotopes.

Isotope-production processes

The radiocarbon process--The best-known process occurs when a neutron is absorbed by a nitrogen nucleus to form radiocarbon. The process may be written

$$n^1 + N^{14} \rightarrow N^{15*} \rightarrow C^{14} + p^1 + Q \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

which is followed by a beta-decay

$$C^{14} \rightarrow N^{14} + e^- \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

thus returning the nucleus to the original N^{14}. No new isotope is formed in this process. The proton emitted in process (1) slows down, picks up a vagrant electron, becomes neutral hydrogen, and is then most probably attached by oxygen to form water. Since water is already an abundant substance, and only a trivial amount is so added, this process adds nothing new. This situation has been understood for a decade and is mentioned only for completeness.

The tritium-helium-three process--Neutrons can also interact with nitrogen to form tritium, according to the process

$$n^1 + n^{14} \rightarrow T^3 + C^{12} + Q \ldots\ldots\ldots\ldots \quad (3)$$

and the tritium beta-decays into helium three according to the process

$$T^3 \rightarrow He^3 + e^- \ldots\ldots\ldots\ldots \quad (4)$$

which process has a half life of around 12.5 years. This process was pointed out in 1950 [KORFF, 1950], and the presence of tritium in nature was subsequently established by Von GROSSE and Others [1951]. The presence of tritium opens up the possibility of a new dating process for natural substances, with a much shorter period than the well-known radiocarbon process.

At this point it becomes appropriate to point out that another process is also operative, which leads to the formation of tritium. This occurs in water, according to the process

$$n + D \rightarrow T + Q \ldots\ldots\ldots\ldots \quad (5)$$

This process occurs when a deuteron captures a neutron. Deuterons exist in nature in the natural abundance of 10^{-4} times the number of protons [CORK, 1950, appendix]. Since most of the hydrogen in the atmosphere and oceans is in the form of water, we can say that one molecule in each 10^4 is an HDO molecule instead of an H_2O. Neutrons in water will be captured by the protons to form deuterons. The rate of formation of tritium, q (T), in water is therefore given by

$$q\ (T) = q(n)\ \sigma\ (T)\ N(D) / \sigma\ (D)\ N(p) \ldots\ldots\ldots\ldots \quad (6)$$

where q(n) is the rate of production of neutrons, σ(T) is the cross section of the process (5), N(D) is the number of deuterons per unit mass or volume, and σ(D) is the cross section for the capture of neutrons by protons to form deuterons, N(p) being the number of protons. The ratio N(D)/N(p) is 10^{-4}, the natural abundance ratio. The ratio of the cross sections is at least 10:1 in favor of deuteron formation, so that numerically q(T) is roughly 10^{-5} q(n).

Eq. (6) assumes that only two processes are in competition. It will be valid if all other processes occur with a rate small compared to process (5).

Since q(n) is about 10^{-5} neutrons per gram per second at sea level, we have for the rate of production of tritium, and hence He^3, around 10^{-10} per gram per second. Over a total of 10^{17} seconds (3×10^9 yrs) the total production will be 10^7 atoms of He^3 per gram. Since a gram contains around 3×10^{22} molecules of water, the fractional amount of He^3 will be one part in 3×10^{15}.

Further, since the production discussed is in a gram or cm^3 of water at sea level, and since the rate of production of neutrons falls off rapidly with depth, production will take place in the top layers only. Indeed, about 87 pct of all the neutron production takes place in the top three meters of the ocean.

Mixing will reduce the concentration. If the average ocean depth is taken as 3×10^5 cm and the production is assumed to occur in the top 300 cm, then the average concentration will be reduced by a factor of 1000.

The number of deuterons produced by the capture of cosmic-ray neutrons by protons in water be 10^5 times greater. But this number is far less than the actual deuteron concentration. Hence it seems clear that present cosmic-ray intensities cannot have produced any substantial fraction of the deuterium in the sea.

Consider next processes in the atmosphere. The total number of cosmic-ray neutrons produced per cm^2 column in the atmosphere is about ten per second [MONTGOMERY and TOBEY, 1949]. If we use (6) and express the competition between processes (1) and (3) in the atmosphere, we shall have about one atom of tritium per cm^2 column per second. Over 10^{17} seconds, we then have 10^{17} atoms of He^3 mixed among the other atoms in the column. As the homogeneous atmosphere is a column eight km long, there will be $8 \times 10^5 \times 2.7 \times 10^{19}$ or 2.17×10^{25} atoms or molecules in the column, or a concentration of one part in some 2×10^8. Now it is known that He^3 is present in the atmosphere in about the amount of one part in 10^7, so we see that the present rate of production is almost enough (falling short only by a factor of 20) to account for the present He^3 content.

There are two factors which would tend to increase the amount of tritium. One of these is that the intensity of cosmic radiation, and hence the rate of production of neutrons might have been higher at some time in the geologic past. Within moderate limits, this does not appear at all unreasonable as an assumption, for if cosmic radiation is of galactic origin, then at some time in the past when there was more condensed and hotter matter present the radiation generating mechanisms might have been more active than today.

The second possibility invoking action in the past assumes that at a time when the Earth was warmer the atmosphere contained much more water vapor, and process (5) might have been operative at a much higher rate than at present.

With further regard to the cosmic-ray intensity in earlier times, it should also be pointed out that the present radiocarbon studies imply that no substantial change in this intensity has occurred within the past 30,000 years or so. Indeed, had the intensity been ten times its present value, 100,000 years ago, radiocarbon data would reveal the fact. Still, had the changes been in effect 10^6 years ago, no traces would have survived in the radiocarbon concentration. But in the He^3 content they indeed might. We can therefore use the He^3 content to give us a maximum value which the integrated cosmic-ray intensity over most geological time could have attained. This value is, as we pointed out above, some 20 times the present value. Had the cosmic-ray intensity been greater than this at any time, we should find more He^3 than we do. This argument extends back far enough in the Earth's history to reach that time when the Earth's atmosphere was much warmer than it is today, and the average velocity of air molecules was closer to the escape velocity. An increase of 100° C would increase the rate of helium loss by escape by an appreciable factor. However, such a temperature regime could not have obtained since the seas were formed some 2 to 3×10^9 years ago.

Other isotope-building processes--A summary of all possible isotope-building processes leaves only a few which need further discussion. Most such processes, arising from the capture of cosmic-ray neutrons by nuclei, are of small cross section compared to processes (1), (3), and (5) cited above. Hence they will not have added much. For example, it is possible to compute the amount of O^{17} formed by the (d, p) process in ordinary oxygen. The amount so formed is the number of neutrons times the yield. The number of deuterons produced in cosmic-ray stars is 0.3 times the number of neutrons, and the yield will be around 10^{-4} (d, p) processes per deuteron. We shall therefore have about 10^{-4} such processes per cm^2 column per sec, or, over a time of 10^{17} sec, around 10^{13} atoms of O^{17}. This is to be compared to a fraction of 4×10^{-4} out of a number $0.2 \times 2.1 \times 10^{25}$, atoms of O^{17}, the natural abundance of this isotope. We see thus that this process can account for about one part in 10^8 of the total amount of this heavy oxygen isotope.

Similarly for nitrogen 15, no important amount is added, for the two much more probable reactions when nitrogen captures neutrons are (1) and (3). Similarly, argon capturing neutrons produces S^{37}, which beta-decays with a five-minute half life to Cl^{37}, the second most abundant isotope. Here again the net effect is a trivial addition to a common substance. Since the other isotopes of oxygen and nitrogen other than the common ones 16 and 14, respectively, are so rare, reactions with them will not add appreciably. None of these reactions have large cross sections, and no important fractions of existing isotope ratios are thus formed.

Neutrons may also be captured by silicon in the ground [KORFF, 1940], by sodium in the salt in the oceans, and by aluminum in the ground. In these cases we have, for the abundant isotope of Si, namely, Si^{28}, an (n, gamma) reaction forming Si^{29} which is present in natural silicon to 4.7 pct anyway. Reactions with Al^{27}, the only common isotope, is the (n, gamma) resulting in Al^{28} which beta-decays after 2.4 minutes to the common silicon isotope Si^{28}. Neutrons captured by Na^{23} form the well-known 14.8-hour radiosodium, which eventually becomes Mg^{24}, again the common isotope. Mg^{24}, when neutron capture occurs, goes by the (n, gamma) process to Mg^{25}, which exists in nature to an abundance of around ten per cent. Hence we may conclude that neutrons do not appreciably alter the isotope ratios of the common substances in the Earth's crust.

Note added September 18, 1953--One problem regarding the Earth's crust is the following:

Because of the very large cross section of the lithium reaction for slow neutrons, does this effect contribute appreciably to the changes in isotope distribution? The question may be answered as follows. A gram of Li contains about 10^{23} atoms of Li. The natural abundance of lithium is not great, being listed in the tables as less than 0.01 pct in the Earth's crust. The average gram of material will therefore contain less than 10^{19} lithium atoms. The number of Li reactions occurring per unit time will then be equal to the rate of production of neutrons, multiplied by the probability that a neutron will be captured by this reaction. This probability will be the number of Li atoms per gram times the cross section in appropriate units. The reaction occurs for the Li^6 isotope, whose abundance in natural lithium is 7.4 pct. The reaction gives rise to a triton plus an alpha particle. The cross section is listed by Bethe as 70×10^{-24} cm^2 for ordinary lithium for thermal neutrons, (or 900×10^{-24} cm^2 for the Li^6 isotope alone). Taking the density of Li as 0.5 g/cm^2, a neutron passing through a gram of matter containing 10^{19} Li atoms has a probability of 3.5×10^{-4} of being captured per traversal. As there are 10^{-5} neutrons per gram per second produced at sea level, there will be 3.5×10^{-9} such captures per gram per second. Over 10^{17} seconds, a total of 3.5×10^8 Li atoms could have experienced this reaction. This is one part in 10^{-11} of the original sample, so this effect will be of no importance in altering distributions. Indeed the actual number of reactions will be smaller because of competition with other processes. The tritons added in this manner will eventually become He^3, but comparing the number with the amount of He^3 produced in the atmosphere by reaction (3) the addition is seen to be inappreciable.

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INTENSITY DISTRIBUTIONS IN NITROGEN BANDS EXCITED IN AURORAS AND BY HIGH-ENERGY PROTONS AND HYDROGEN ATOMS

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Abstract--Nitrogen negative and second positive band spectra have been excited by 100-kv protons and hydrogen atoms from the Rice Institute van de Graaff accelerator. The intensity distributions in the vibrational bands are compared with spectra produced in controlled laboratory experiments by canal rays and electron impact, with auroral spectra, and with results of theoretical calculations. Excitation of second positive bands by high-energy neutral hydrogen atoms and of the negative bands by both neutral hydrogen and protons show the expected marked increase in the rate of population of high vibrational states. Theories for the excitation of the auroral bands are discussed in the light of these results and of theoretical considerations.

Introduction--The primary source of energy for auroras is generally presumed to be a beam of charged particles emanating from the Sun. Principal evidence involves doppler shifts in the spectrum, the spatial distribution of auroras relative to the Earth's magnetic field, and the reproducible time delay that exists between the appearance of an intense solar flare and the onset of magnetic storms and auroras. Observation of MEINEL [1951] of shifts to the violet in the hydrogen Balmer spectrum in the aurora gave final confirmation to the reports of VEGARD [1939] and GARTLEIN [1951] that hydrogen lines in the aurora originate from protons traveling at high speed from the Sun. However, the relationship between this solar hydrogen stream and the rest of the auroral spectrum is still an open question and is the subject of this report. An experimental determination of the intensity distribution produced by high-energy protons will be compared in Figures 1 and 2 with the results of theoretical and laboratory studies of excitation mechanisms in N_2 spectra and with several recent observations of intensities in auroral bands.

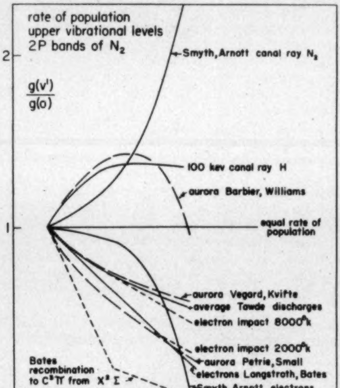

Fig. 1--Relative rates of population of upper vibrational levels in the second positive bands of N_2, determined from theoretical calculations (short dashes), auroral observations (long dashes), and laboratory experiments (solid lines)

In excitation of a diatomic molecule by electron impact, the probability of excitation of rotational energy is negligible by conservation of momentum. Also, the collision is very likely to be elastic unless the energy is high enough to excite an electronic transition, in which case the Franck-Condon rule accurately describes any vibrational change which will occur. However, a heavy particle, such as the solar hydrogen, may excite both vibration and rotation, with or without electronic excitation. Hence we may seek in auroral spectra the effects of proton- or hydrogen-atom excitation through the rotational- and vibrational-intensity distributions in the nitrogen molecular bands. Unfortunately the theory cannot tell us quantitatively how much vibration to expect from impact of a fast ion or atom on a diatomic molecule, except for collisions at near thermal energies. In general we expect a maximum in the cross section for excitation of vibration by atom impact at energies well above thermal but below the energy region of the protons of the upper atmosphere.

As regards excitation of electronic states by fast ions or atoms, the cross sections are approximately equal to those for impact by electrons of the same velocity [MOTT and MASSEY, 1949, p. 271]. This includes not only excitation to bound states but also excitation into the continuum (that is, ionization, but not charge exchange). Thus an

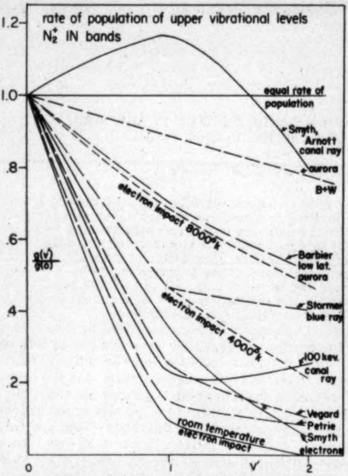

Fig. 2--Relative rates of population of upper vibrational levels in the first negative bands of N_2^+, determined from theoretical calculations (short dashes), auroral observations (long dashes), and laboratory experiments (solid lines); calculated curves for electron impact are for simultaneous ionization and excitation [BATES, 1949]; "B + W" refers to BARBIER and WILLIAMS [1950]; for Störmer data, see HARANG [1951, p. 76]

83-kev proton is roughly equivalent to a 45-volt electron. If the ion or atom velocity is too low, the collision will be adiabatic, and the cross section for excitation or ionization by impact or charge exchange will be very small. Quantitatively, if a is the impact distance, v the velocity of the impinging atom, and ΔE the net change in internal energy of the system, the collision is adiabatic if

$$a\,\Delta E/hv \gg 1$$

For an ion traveling with a velocity below that giving the maximum cross section for ionization, charge exchange is much more probable than ionization by ion impact, the net value of the excitation energy (ΔE) being much smaller. Above the energy giving the maximum cross section, the probability for impact excitation decreases slowly (as $E^{-1} \log E$) for optically allowed transitions, more rapidly (E^{-1}) for forbidden but not intercombination transitions, and very rapidly for intercombination transitions. The latter process can occur only by charge exchange, the incident particle contributing or removing the required spin. Hence the proton cannot excite intercombination transitions, provided LS coupling prevails in the atom being excited [MASSEY and BURHOP, 1952, p. 152]. In general a neutral atom will have a higher probability for producing excitation than an ion of the same speed, as has been demonstrated experimentally by DÖPEL [1933].

The energy of the assumed beam of solar protons is quite uncertain. The three principal sources of evidence give inconsistent results. The time delay between the appearance of a large solar flare and the occurrence of magnetic storms (with aurora) on the Earth, which is 21.5 ± 2.1 hours [NEWTON, 1944; HARANG, 1951, p. 143], gives a proton velocity of 1.9×10^8 cm/sec (19.2 kev) assuming straight paths and uniform velocity. KIEPENHEUER [1952] computed a proton velocity of 1.6×10^8 cm/sec. Second, in order to penetrate the Earth's atmosphere to 80 km, a proton must enter with a velocity of around 10^9 cm/sec, as estimated by MEINEL [1952]. This corresponds to an energy of 521 kev, but the figure is only approximate since the proton range-energy curve in atomic oxygen is unknown (see below). Third, the doppler shifts in auroral Balmer lines show that most of the hydrogen atoms radiate at a velocity of about 5×10^7 cm/sec, but the violet wing of the line shows that some of the radiating atoms have speeds of 3.3×10^8 cm/sec (57 kev) [MEINEL, 1951]. KIEPENHEUER [1952] has computed 2 to 3×10^8 cm/sec. As Meinel points out, this must be a lower limit to the velocity of the protons when they enter the atmosphere, as the protons must lose energy until they reach a speed at which by charge transfer they become neutralized and begin to radiate Balmer lines.

The fact that Balmer radiation begins to occur at energies as high as 57 kev follows from the fact that for charge transfer to produce H_β, capture must be into the n = 4 level in hydrogen. This is within a volt of the ionization potential. Thus the ΔE value is almost the same as it would be for straight ionization. The maximum for this process (capture into high bound states) is probably well below 57 kev. This capture has been most recently studied by DIETERICH [1953], who observed the emission of Balmer lines from protons of only two thousand volts in helium. The evidence suggested that this energy was well below the energy for maximum probability of this process. For H and O, the ionization potentials (13.595 and 13.614 volts) are so nearly identical that charge transfer into the ground state will have its maximum within a few volts of zero. (For this reason, it is possible that the range of 100-kev protons in atomic oxygen may be longer than in laboratory air, thus making Meinel's estimate of the energy (521 kev) needed to penetrate to 80 km altitude an overestimate (as it seems to be, compared with solar-terrestrial time delays). Because of the near equivalence of the ionization potentials of H and O, the charge-transfer cross-section drops with increasing energy from a maximum near zero [see MASSEY and BURHOP, 1952, p. 519] and should be quite small at 100 kev. Since charge transfer is a major source of energy loss for fast protons in air, an atmosphere largely composed of atomic oxygen would be more transparent to fast protons than would the molecular oxygen and nitrogen in which range-energy curves are made. The complete dissociation of oxygen which occurs around 100 km and the diffusive equilibrium which prevails above this altitude produce an atmosphere in which atomic O may be the predominant constituent (that is, MITRA, Proc. Conf. on Ionospheric Physics, State College, Pa., July, 1950).) For capture into the n = 4 level, the maximum will be about what it would be for an excitation collision without transfer. This is the energy at which the proton has the same speed as the 3s electron (0.73×10^8 cm/sec) giving a proton energy of about three kev [MEINEL, 1951]. Note that this agrees with the 5×10^7 cm/sec velocity obtained from the doppler shift of the peak of the Balmer line observed by Meinel.

Therefore, our spectroscopic studies were made with 100 to 150 kev protons accelerated into air at reduced pressure. Previous quantitative experiments on excitation of vibrational energy in diatomic molecules by impact of a beam of ions were confined to lower energies. SMYTH and ARNOTT [1930] studied excitation of molecular nitrogen bands excited by 6000-volt nitrogen canal rays and, for comparison, by 700-volt electrons. Their results showed a very striking increase in population of higher vibrational states in the canal-ray experiment over the distribution obtained by electron impact. However, the intensities were estimated visually from uncalibrated plates, yielding qualitative results. VEGARD and RAASTAD [1950] have performed a very similar experiment using canal rays from nitrogen and from a mixture of nitrogen and helium. They found results in qualitative agreement with Smyth and Arnott, although their measured band intensities within each progression disagree with the known transition probabilities.

Experimental--The spectra to be described in this paper were excited by high-energy protons from the van de Graaff accelerator of the Rice Institute [SHALEK, BONNER, and BRANSCOMB, 1952]. The protons passed through a thin mica foil into a chamber (Fig. 3) filled with air at a few millimeters pressure. Spectra were obtained in the blue and ultraviolet regions on 103-0 plates.

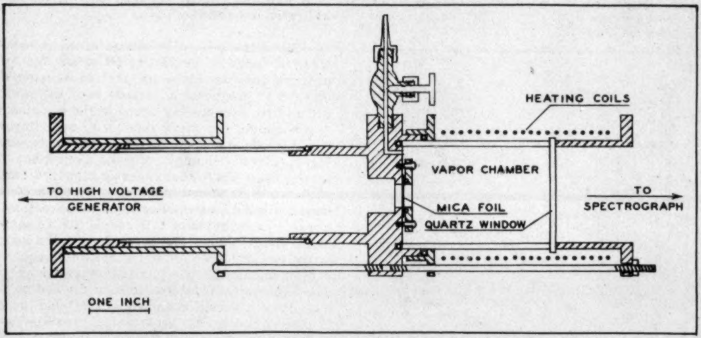

Fig. 3--Collision chamber containing low-pressure air bombarded by high-energy protons from the van de Graaff accelerator of the Rice Institute

A typical spectrum is shown in Figure 4. Twenty-seven members of the second positive (2P) bands of N_2 and seven members of the first negative (1N) bands of N_2^+ appear. Two or three weak features not conclusively identified are probably OH or weak N_2 2P bands. Although there are two coincidences with the Y bands of the night sky and aurora reported by BARBIER and WILLIAMS [1950], failure of other Y bands to appear discourages this identification. No atomic lines appear on the plates, nor do any oxygen spectra, atomic or molecular. The absence of these radiations will be explained below. The absence of any NO beta bands shows that secondary excitation processes may be neglected. Since the measured intensities were to be compared with other laboratory and auroral spectra, 19 N_2 2P bands were selected which occur in all the spectra.

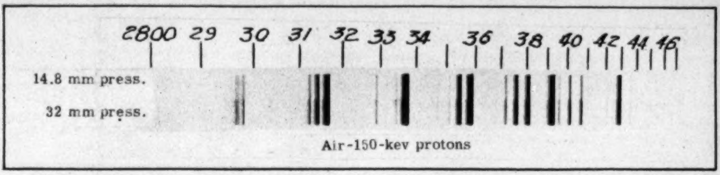

Fig. 4--A typical air spectrum obtained by high-energy-proton and H-atom bombardment; photographed on 103-0 plates, the spectrum shows only 2P and 1N bands of nitrogen; no atomic lines or oxygen spectra

The intensity in a vibrational band (v′, v″) is given by

$$I(v',v'') \propto g(v')\, p(v',v'')\, \nu^4(v',v'') / \sum_{v''} p(v',v'')\, \nu^3(v',v'')$$

where g(v′) is the rate of population of the upper state v′, ν is the frequency of the radiation and p(v′, v″) is the fractional transition probability. From this relation, the p's may be determined experimentally, for

$$p = (I/\nu^4)/\sum_{v''}(I/\nu^4) \qquad \text{since } \sum_{v''} p = 1$$

This has been done by TAWDE [1934], who determined the p's from careful studies of four different types of glow discharges and arcs through nitrogen. His results are averaged by BATES [1949] with Bates' calculations of the p's. The transition probabilities have also been computed at the HARVARD COMPUTATION LABORATORY [1950] using the method of Manneback. These calculations are more extensive than Bates', and agree well with his results.

Since there is little change in the internuclear distance in the 2P and 1N bands, the Δv progressions are close together in wavelength, so each v′ progression extends over the same wavelength range. Any error in the wavelength dependence of the plate sensitivity or calibration would produce erroneous p's in each progression irrespective of the nature of the excitation. In those cases where there was no standard lamp calibration or where other errors appeared, the known p's were used to produce a correction curve. An example of this correction is shown in Figure 5. Using Manneback's p's, the intensities I(v′, v″) are calculated assuming equal rate of population, g(v′), of all upper states v′. The experimental intensities are divided by the calculated intensities for equal g(v′) and the ratio is plotted against λ. Each v′ progression is plotted separately, and Figure 5 shows that each progression requires roughly the same correction curve. The first negative bands from the same plate require the same correction. The fact that the lines are parallel but separated shows that g(v′) is not independent of v′. Some of the data, treated this way, gave horizontal lines, showing that no correction was needed.

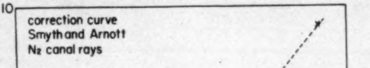

Fig. 5--Typical plot illustrating the method for correcting experimentally obtained intensities for errors dependent on wavelength; the data are required to conform with known transition probabilities; the curves are expected to have the same slope, but not to coincide unless the upper vibrational levels are populated at equal rates

Since a Boltzmann energy distribution does not obtain for any of the data, the corrected intensities are plotted by calculating the experimental rates of population

$$g(v') = \sum_{v''} I(v'v'') \cdot \left(\sum_{v''} p\nu^3 / \sum_{v''} p\nu^4\right)$$

and plotting the ratio g(v′)/g(0) against v′. Small correction factors of 0.96 and 0.98 are applied to correct for the effect of neglected bands. Figure 1 gives the population rates for the N_2 2P bands, and Figure 2 the same data for the N_2^+ 1N bands.

Results--In Figure 1 the distribution produced by electron impact at room temperature as calculated by BATES [1949] and measured by Langstroth is shown as well as calculations of the effect of electron impact at 2000 and 8000° K. The average of Tawde's four different discharges shows rather high vibration resulting from the many complex excitation processes in these sources. The quantitative unreliability of Smyth and Arnott's data is shown by the large discrepancy between their electron impact data and the work of Langstroth and Bates.

The 100-kev hydrogen canal ray shows strikingly high vibration. It is to be expected that Smyth and Arnott's spectra should show even higher vibration since their canal ray, N_2^+, had the same mass as the target molecules.

Of the negative bands of N_2^+ only seven are seen, and the rate of population data are poorer than for the 2P bands. The results, shown in Figure 2, show the same error in Smyth and Arnott's electron impact data as in Figure 1. It is significant that the 100-kev hydrogen canal ray shows a less striking increase in the population of higher vibrational states in the 1N bands than in the 2P bands, although in both cases the distribution is clearly higher than that obtained by electron-impact ionization and excitation (shown in the short dashes curves).

The most striking aspect of the auroral data in Figures 1 and 2 is the very great difference between the populations observed from different stations. Except for the work of PETRIE and SMALL [1952a] at Saskatoon, the auroral data for both 1N and 2P bands show distributions which are clearly higher than could be produced by electron impact at any reasonable gas temperature. The BARBIER and WILLIAMS [1950] data were obtained at Fairbanks, the VEGARD and KVIFTE [1945] spectra at Tromso and Barbier's low-latitude auroral N_2^+ spectra [BARBIER, 1947] at l'Observatoire Saint Michel in southern France. In reporting their work, Petrie and Small conclude: "The population rates derived from our intensities differ appreciably from those of Vegard, and cannot be reconciled with the theoretical rates unless the process of excitation from the ground electronic level operates and the vibrational temperature is less than 500° K."

Discussion--The following four points should be noted.

(1) Absence of bands of O_2^+ -- O_2^+ bands are weak in the aurora and absent in the spectra produced by passage of 100-kev hydrogen canal rays through air. (Several O_2^+ first negative bands have recently been identified in the auroral spectrum by PETRIE and SMALL [1952b] and by VEGARD [1952], but their intensities are very much lower than the 1N N_2^+ bands.) Auroras at high altitude do not exhibit these bands, because the oxygen is dissociated. However, the maximum auroral luminosity for many-colored draperies [HARANG, 1951, p. 143] lies at 97 km, below the altitude (105 km) at which the oxygen is only 50 pct dissociated [MITRA, 1947]. Consequently, we might expect the lower fringes of auroral draperies to be fringed with strong O_2^+ bands. Similarly, O_2^+ bands might occur in the laboratory excitation of molecular oxygen by fast protons. They do not occur for two reasons. The neutralized H atoms which penetrate to 100 km altitude are too slow to excite bands of such large ΔE (17 ev). Instead they will excite lower O and N_2 levels. Any protons reaching this altitude might be expected to ionize and excite O_2^+ bands by charge exchange. But the Σ_g^4 level cannot be excited by charge transfer from the ground state of the atom or by charge exchange with the ground state of the ion. Hence the first negative O_2^+ bands cannot be excited in this way (see Fig. 6). While the π_u^2 state can be excited by charge exchange from the ground state, the second negative bands arising from this state lie in the ultraviolet and are much less intense, because of the large change in the internuclear distance involved, which distributes the available energy into a great many bands. Furthermore, the dissociation which suppresses the O_2 Schumann-Runge bands when excited at low pressure also mitigates against the O_2^+ 2N bands [BRANSCOMB, 1950]. Additional vibrational energy produced through excitation by heavy-particle impact accentuates this effect. Thus, neither of the O_2^+ band systems are observed in our laboratory spectra of air excited by high-energy protons. The weak 1N O_2^+ bands observed in the aurora by PETRIE and SMALL [1952] must then be excited by charged-particle impact without exchange. Since these bands cannot originate at high altitude (where the hydrogen beam is sufficiently energetic for impact excitation of O_2^+ spectra), they must be excited by electron impact in a secondary discharge phenomenon.

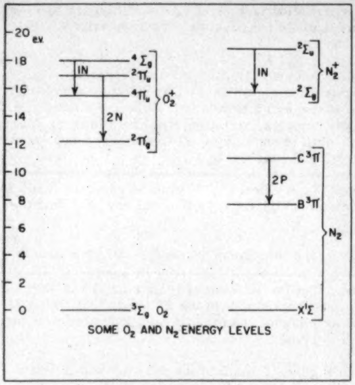

Fig. 6--Certain energy levels of O_2 and N_2 showing emission bands and the multiplicity changes required in excitation to these levels from the ground states

(2) Excitation of vibration in N_2 and N_2^+ bands--By the same argument invoked in the above paragraph, the 2P bands of N_2 cannot be excited by proton impact, but require electron exchange, therefore electron or neutral atom impact. The 1N bands of N_2^+ are more likely to be excited by proton impact and charge exchange, although they can also be excited by neutral atoms or electrons, since charge exchange reduces the change in internal energy ΔE from 18.75 volts to 3.17 volts. Therefore, as the 100-kev proton beam enters the air sample, the beam will first lose energy by impact ionization, producing N_2^+ 1N bands and unexcited ions, not with very high vibration because of the short wavelength of the proton at this speed. (WIEN [1914] found that in optical excitation by fast atoms, the target atoms showed almost no doppler effect, while the incident-beam doppler line remained very sharp.) As the 100-kev proton beam loses energy, the 1N bands of N_2^+ are produced by charge exchange with some excitation of vibration. Then when the proton beam has been largely neutralized and is slowed down to a few thousand volts or less, the intercombination excitation of the 2P bands occurs with increasing vibrational temperature. Figures 1 and 2 show that the high vibration is more marked in the intercombination excitation of the 2P bands (Fig. 1) than the charge-exchange-excited 1N bands (Fig. 2). There seems to be a similar effect in the auroral data. It is also observed in the aurora that the ratio of intensity of 1N bands to 2P bands increases with altitude in conformity with this notion.

(3) Rotational temperatures--In excitation by 100-kev protons, the rotational temperatures could only be estimated, giving between 700 and 1000° K. for the 3914 A and 4278 A bands of the 1N system. This high rotation is to be expected in excitation by heavy-particle impact. However, uniformly low rotational temperatures are observed in the auroral 1N bands, which are fully allowed. A study of the induction of rotation by exchange excitation is needed to clarify this point. GARTLEIN and SPRAGUE [1952], however, have observed that in auroras with strong H lines there is an increase in the rotational temperatures of the first positive bands of N_2. No temperatures were measured. They noted that the branch maxima became more separated as the hydrogen lines strengthened. In the aurora the 1P and 2P of N_2 are probably excited by the same mechanism, both requiring exchange excitation.

(4) Auroral excitation--Although the wide differences in auroral vibrational intensity distributions reported by different workers discourage generalization, most of the data are characterized by higher vibration than can be explained by electron impact at a plausible gas temperature. It is quite possible, if not likely, that more than one mechanism is responsible for auroral excitation of nitrogen bands, and that the balance between these mechanisms varies with time and location.

Both MEINEL [1952] and GARTLEIN [1952] have observed that the 1N bands are closely correlated in intensity changes with the H_α line, while the oxygen green line and the second positive bands seemed to persist after H_α died out. Gartlein noted that the peak of N_2^+ always follows or coincides with the peak of H_α intensity, suggesting that the N_2 is ionized, or ionized and excited, by proton impact and exchange.

OLDENBERG [1952] has applied the principles discussed in this paper to the excitation processes in sunlit auroras. He proposes the idea that nitrogen molecules are ionized by charge transfer and excited by fluorescence, while the forbidden oxygen lines are excited (by exchange) by the slow electrons which accompany the protons from the sun. These electrons do not have sufficient energy to penetrate to the altitude from which the N_2 2P bands are radiated, unless the particle beam from the Sun has much higher energy on occasion than is generally supposed.

Understanding of auroral excitation process will not be obtained until more quantitative comparison of the field observations of different workers is possible, nor until a quantitative understanding is gained of the fundamental atomic processes involved.

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VELOCITY DISTRIBUTION AND THE BOUNDARY LAYER AT CHANNEL BENDS

H. A. Einstein and J. A. Harder

Abstract--An analysis of the accelerating forces available within a relatively wide shallow channel bend shows that the existence of higher velocities near the outside bank requires, in addition to the helical flow pattern commonly observed, that the outward flowing upper layers be unaffected by bed shear. Velocity measurements made in a model channel bend at a point unaffected by entry conditions have confirmed this requirement, indicating that the inward flowing bottom layers move within a boundary layer similar to those found near the surface of airfoils. The parameter $(r/v)\,dv/dr$, which should have the value -1 for free vortex flow and $+1$ for flow with constant angular velocity, exceeded $+4$ in these experiments and was found to be directly proportional to the friction factor. Theory developed indicates that this parameter is directly proportional to the width-radius ratio also in those regions beyond the effect of entry conditions.

The problem--In his recent thesis study, the junior author of this paper asked himself if it would be possible to find a theory from which the cross distribution of flow velocities in a river bend could be predicted and which parameter or parameters would enter this description. His own experiments, as well as a survey of the pertaining literature, showed that the transition from a straight channel into a bend is very complicated and, in many cases, not even continuous. The present study was thus restricted to the equilibrium distribution in a continuous bend. Such an equilibrium was apparently reached in the specially constructed model bend after an entrance section of 90°.

It is generally known that the cross distribution of velocities in an open channel bend is closely related to the secondary currents developed in such bends. The secondary currents in turn are to a large degree responsible for the scour patterns in alluvial stream bends and their development into complete meander patterns. It is hoped, therefore, that studies like this may help to develop eventually a theory of river meandering.

The theory--Potential flow theory, that is, the flow theory of ideal, frictionless fluids, permits the prediction of a cross distribution of velocities in such a bend if it is assumed that a straight channel reach with even velocity distribution precedes it. In the straight approach channel the specific energy (the energy per unit weight of fluid) is, by definition, constant. Assuming an ideal fluid, this specific energy must have the same value after the water has entered the various parts of the bend and must thus be constant over the cross section in the bend. At the entrance into the bend the change of flow from the straight approach into the curved flow of the bend is affected by a series of waves originating from the banks and accelerating the various flow filaments. Let us assume for the time being that a system of such waves can be generated which leaves the flow after a given transition reach of the bend in a new state of equilibrium flow in which all the wave effects have cancelled out and a simple concentric flow pattern is left which shows only tangential velocities, while all radial velocity components are identically zero.

The radial velocity distribution for this ideal fluid in equilibrium bend flow can be derived from the equilibrium condition of a fluid element in connection with the Bernoulli equation. For this and later analyses a cylindrical coordinate system will be utilized in which the z axis coincides with the center of curvature of the channel centerline, r is the radial distance outward, and θ is the angular displacement about the z axis (see Fig. 1). Corresponding velocity components are w vertically, u radially, and v tangentially. Defining ρ as the fluid density and p as the fluid pressure, the equilibrium condition for curvilinear flow is

$$dr\,(dp/dr)\,r\,d\theta\,dz = \rho r\,d\theta\,dr\,dz\,v^2/r$$

or shortened

$$dp/dr = \rho v^2/r \;.\;.\;.\;.\;.\;.\;.\;.\;.\; (1)$$

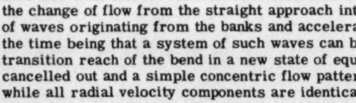

Fig. 1--Elemental fluid volume in cylindrical coordinates

Within a horizontal plane the Bernoulli equation takes the form

$$p/w + v^2/2g = \text{constant}$$

Differentiating with respect to r

$$dp/dr = -(w/g)\, v\, dv/dr = -\rho v\, dv/dr \quad \ldots\ldots\ldots\ldots\ldots\ldots\ (2)$$

Eliminating dp/dr from (1) and (2) one obtains

$$v/r = -\, dv/dr$$

or

$$(r/v)\, dv/dr = -1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (3)$$

Eq. (3) may be integrated into rv = a constant, the generally known equation of the potential-flow vortex.

The parameter $(r/v)\, dv/dr$, which has, according to (3), the value -1 for the potential-flow vortex, has proved to be very convenient for the description of the velocity cross distribution in channel bends and may easily be determined as the slope of a curve of velocity v against radius r in a log-log graph. A previous study [LI, 1950] has shown that internal friction between cylindrical fluid layers may account for values of this parameter between -1 and $+1$, but no values larger than $+1$ can be predicted by this approach. Unfortunately, all observed distributions show values well in excess of $+1$ and thus need a different explanation.

In an attempt to describe the flow conditions in a given channel, it is necessary to introduce in the mathematical description all important physical aspects of the flow. The most characteristic single feature of this flow is the "secondary current" which forms a circulatory motion towards the outside at the surface and towards the inside at the bottom. The cause of this circulation has been known for a long time to be the difference between the centrifugal acceleration in the fast-flowing top layers and the slow-flowing bottom layers of the main flow. The effect of this circulation back onto the cross distribution of the main flow does not seem to have been studied previously, and is the subject of the present study.

The major difficulty of the problem consists in the mutual interdependence between the main flow and the secondary current. Neither can be predicted independently of the other. It became necessary to describe the flow through the bend as a three-dimensional problem combining main and secondary flows. After many unsuccessful attempts, an idealized flow pattern was used for the description, based on the observed secondary current pattern as shown in Figure 2.

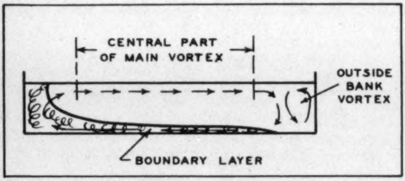

Fig. 2--Secondary currents in the channel cross section

While the smaller vortex, apparently caused by the outside bank friction, is of considerable interest in itself, this paper is concerned with the velocity distribution within the main vortex which is related only indirectly to any bank effect.

Within the center part of the main vortex the flow was assumed to be divided into two layers: (1) an upper layer with an outward radial velocity U and a tangential velocity V, and (2) a lower layer with a corresponding inward radial velocity U' and tangential velocity V'. The upper layer, being much thicker, dominates the observed radial velocity distribution; however, the lower layer plays a very important part in determining this distribution.

In analyzing the velocity distribution within the main vortex the cylindrical coordinate system described above was used and the following assumptions were made: (1) The section was far enough downstream from the entrance so that equilibrium velocity distribution had been attained; that is, that the velocity pattern did not change from section to section or with time. (2) Vertical velocity components were negligible. This restricts the validity of the analysis to the center part of the main vortex.

Restricting our attention for the moment to the center part of the upper layer, we may equate the product of mass per unit volume of fluid and its tangential acceleration to the sum of tangential forces acting on the unit volume. If U and V are the radial and tangential velocity components in the upper layer and assumption (2) is true, the equation, in cylindrical coordinates, reduces to

$$dV/dt = \partial V/\partial t + U\partial V/\partial r + (V/r)\partial V/\partial\theta + UV/r = (1/\rho)\Sigma F_\theta$$

wherein ΣF_θ represents the sum of tangential forces acting on the unit volume. Under assumption (1) all derivatives with respect to time and angular displacement θ are zero, and the equation is reduced further to

$$U\partial V/\partial r + UV/r = (1/\rho)\Sigma F_\theta \qquad (4)$$

The sum of the tangential forces acting per unit volume, ΣF_θ, can be conveniently related to the product of the unit weight, w, of water and the tangential surface slope, minus whatever shear forces are acting. In the present discussion we shall define the sum of shear forces acting in terms of the unit weight and a friction slope, s_f. Thus $\Sigma F_\theta = w\ (s - s_f)$. Introducing this expression into (4) we obtain

$$U\partial V/\partial r + UV/r = (w/\rho)\ (s - s_f) = g\ (s - s_f) \qquad (5)$$

In terms of the parameter (r/V) dV/dr this becomes

$$(r/V)\ dV/dr = (gr/UV)\ (s - s_f) - 1 \qquad (6)$$

wherein the partial notation has been dropped.

For uniform flow in a straight channel the sum of shear forces acting on any volume of fluid is equal to ws. Were this the case for the upper layer in bend flow, (6) indicates that the parameter (r/V) dV/dr would have the value - 1. Thus, under the assumptions made, it may be seen that unless the friction slope, s_f, is less than the tangential surface slope, s, the parameter cannot exceed - 1.

Inasmuch as values of the parameter exceeding + 4 were measured, it was necessary to postulate a mechanism whereby the friction affecting the upper layer would be less than the tangential surface slope wherever these large values were observed. As a matter of fact, when experimental values of measurable quantities were introduced into (6), it was apparent that the friction slope for the upper layers was either zero or else very small relative to the tangential surface slope. This would indicate that frictional effects were limited to the lower layer, which would transform it in effect into a boundary layer.

An example of such a boundary layer is observed near the leading edge of a flat plate immersed in a fluid flowing parallel to its sides. Without deriving the equations of boundary layer growth, let us review some of the characteristics of the boundary layer. Although the boundary shear may be rather large near the leading edge, the resultant force is expended at first in overcoming the momentum of fluid near the surface, or within the boundary layer. Outside this layer the fluid moves essentially as in potential flow, displaced laterally by the thickness of the boundary layer, which continuously increases in thickness along the length of the plate as more and more fluid comes under the influence of the shear forces.

If the boundary happens to be the interior surface of a pipe, the layer soon reaches the center and no further development takes place; also a boundary layer may develop along the bottom of an open channel immediately downstream from a well-rounded entry, but it soon grows so as to encompass the entire area up to the surface of the water.

The boundary layer at channel bends--If there is an outward component of velocity U in the surface water, a corresponding inward flow along the bottom must occur. The outer bank, then, must divert high velocity water downward and inward. In effect a continuous flow with an appreciable momentum is directed slantwise inward across the channel bottom. As a consequence, a boundary layer forms and increases in thickness as the water moves from the outer bank, as shown in Figure 2. If the inward component of velocity along the bottom is fairly large, the boundary layer may exist over an appreciable width of channel before it grows sufficiently in thickness to affect the surface water. It is within this width and because of this boundary layer that the radial velocity gradient parameter, (r/V) dV/dr, can have values exceeding + 1.

Quantitative aspects of the radial velocity distribution pattern--By making certain simplifying assumptions, the above theory has been evolved into one which quantitatively relates the value of the radial velocity distribution parameter to other significant parameters of the channel bend. The following is a description of this development.

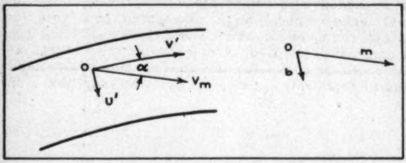

Fig. 3--Velocity components within the lower layer

Figure 3 is a plan view of a section near the outside bank of a relatively wide shallow channel bend. As far as the lower layer is concerned, a line source of fluid exists near the outside edge where water from the upper layer is diverted downward and inward by the outer bank. Consider the fluid entering the lower layer at some point, o, and flowing in the direction labeled m. Its velocity V_m has a radial component U' inward and a tangential component V'; its direction with respect to the channel centerline is given by the angle α. The thickness of the turbulent boundary layer may be shown to vary approximately as the 4/5 power of distance along a streamline; if the variation of shear forces with boundary layer thickness is neglected, the thickness would be directly proportional to this distance. Under this latter approximation, the boundary layer thickness, δ, may be considered to be proportional to the distance m along the streamline from 0. Introducing a proportionality constant C_1

$$\delta = C_1 \, m \quad \ldots\ldots (7)$$

From the figure, the relation between the boundary layer thickness and the radial distance b from the point 0 is

$$\delta = C_1 \, b \, V_m/U' = C_1 \, b \, V'/U' \cos\alpha \quad \ldots\ldots (8)$$

It is evident that a boundary layer, such as described above, can exist only over a finite width of channel. In some cases this width is fixed by the physical boundaries of the channel, and in any case it is related to the width of the main vortex. If this width has the value B, from (8) we may define a mean value for the boundary layer thickness within the vortex

$$\bar{\delta} = (C_2 \, B/\cos\alpha) \, V'/U' \quad \ldots\ldots (9)$$

From (9), together with the equation of continuity, which relates the outward flow in the upper layer to the inward flow in the lower layer under equilibrium conditions, we may obtain an expression for the radial velocity U in the upper layer for incorporation in (6). Thus from continuity,

$$U = \delta \, U'/(D - \bar{\delta}) = [C_2 \, B/(D - \bar{\delta})] \, V'/\cos\alpha \quad \ldots\ldots (10)$$

where $(D - \bar{\delta})$ is the thickness of the upper layer and D is the depth of flow. Incorporating this expression for U in (10) into (6) we obtain for the radial velocity gradient parameter

$$(r/V) \, dV/dr = (g \cos\alpha/C_2) \, (r/B) \, [(D - \bar{\delta})/V \, V'] \, (s - s_f) - 1 \quad \ldots\ldots (11)$$

Although the upper layer experiences acceleration and the lower layer deceleration, the overall flow pattern must be affected by a friction loss. In the present discussion, we shall define this friction loss in terms of the friction factor, f, used in uniform straight channel flow, the hydraulic radius, R, of the cross-section, and the mean velocity $\bar{V}$. In uniform flow these quantities are related to the water surface slope by

$$s = (f/4R) \, \bar{V}^2/2g \quad \ldots\ldots (12)$$

Factoring s from (11) and substituting its value from (12) we obtain

$$(r/V) \, dV/dr = (f)(\cos\alpha/C_2) \, (\bar{V}^2/V \, V') \, [(D - \bar{\delta})/8R] \, (r/B) \, [1 - s_f/s] - 1 \quad \ldots\ldots (13)$$

Simplifying assumptions applied to (13)--In a relatively wide shallow channel the hydraulic radius is nearly proportional to the depth, and if the boundary layer thickness is small relative to the depth, the term $(D - \bar{\delta})/8R$ may be considered a constant. Although the product of the velocity in the lower layer, V', and in the upper layer, V, may not be expected to equal the square of the mean velocity, $\bar{V}^2$, the term $\bar{V}^2/VV'$ should be relatively constant, varying slightly with the bed shear and thus with the friction factor.

The angle α should vary somewhat with the radius of curvature, since it represents a measure of the ratio of crosswise to longitudinal water surface slopes. So far, the experimental work has been confined to a model channel with a constant radius of curvature; under these conditions it is believed that considering $\cos\alpha$ to be nearly constant is justified. Another justification is that α seems always to be less than 45°, and in this range the cosine function does not change as rapidly as its argument. For relatively large radius-to-depth ratios, then, (13) has been simplified to the form

$$(r/V)\ dV/dr = C\ f\ (r/B)\ [1 - s_f/s] - 1 \ldots\ldots\ldots\ldots\ldots\ldots (14)$$

Experimental apparatus--All of the experimental work was conducted in a specially constructed model bend of rectangular cross section four inches deep and 16 inches wide, with a centerline radius of ten feet. Since the bend was entered gradually through a spiral transition section and the radius of curvature was 35 times the maximum depth, the velocity distribution after a further 120° circular section of bend, where the velocity measurements were made, had achieved essential equilibrium. No change in the velocity pattern could be observed between successive reaches within the seven-foot test section.

Velocities were measured using wooden floats, constructed of doweling and weighted at one end. Their length was adjusted so that they floated about 1/16 inch off the bottom. When floating within the main vortex, they were observed to tilt outward, but to remain about the same distance from the inside bank, thus demonstrating that the circulation current was affecting both the upper and lower parts of the float. The velocity measured by this means was assumed to correspond to the average velocity along the path of the float; by placing the float at various radial positions, the crosswise velocity distribution was determined.

Experimental data--The crosswise velocity distribution was determined for flow in a smooth channel bend and in a channel bend which had been artificially roughened by placing expanded metal lath along the bottom. Measurements were made at different depths, which served to vary the Reynolds number in the first case and the relative roughness in the second. The radial velocity gradient, dV/dr, was determined by measuring the slope of a line drawn through a log-log plot of the velocity against radius. A typical plot is shown as Figure 4.

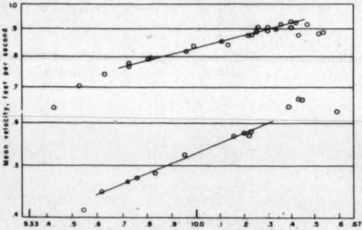

Fig. 4--Radial velocity distribution; upper: smooth bed, depth 0.212 ft; lower: rough bed, depth 0.273 ft

Of the other factors appearing in (4), the radius of curvature, r, was constant for all runs; and the width of the main vortex, since it was restrained laterally by the fixed width of the channel, should be expected to remain constant also. Actually, this width, B, was observed to change somewhat at greater depths of flow due to the fact that the outer bank vortex (see Fig. 2) occupied a portion of the channel width. For the smooth channel this width, B′, was found to be equal to the depth of flow, and for the degree of roughness introduced in the artificially roughened channel it was equal to about half the depth of flow. Accordingly the width of the main vortex was assumed to be equal to the width of the experimental channel less B′. In the central portions of the main vortex, where dV/dr was measured, the upper layer appeared to be completely isolated from the effects of bed shear. Thus s_f was zero and the term $1 - s_f/s$ approached unity. At extreme width-depth ratios, however, the friction slope asserted itself; this phenomenon will be discussed below.

Due to the fact that water surface and bed slopes were on the order of 0.0003, no reliance was placed on slope measurements for determining the friction factor. Instead, the friction factor was assumed to be the same function of Reynolds number and relative roughness as found for straight channels.

Under the above assumptions, (14) can be rearranged to give an expression for the friction factor in terms of the other variables

$$f = C_3 \left[(r/V\ dV/dr + 1\right]\ B/r \quad \ldots \ldots \quad (15)$$

= a function of Reynolds number and relative roughness

In the case of the hydraulically rough channel, the absolute roughness remained the same and the relative roughness was inversely proportional to the depth. For the values of relative roughness employed, the best exponential approximation of the logarithmic relation between friction factor and relative roughness is

$$f = A\ (e/D)^{1/4} \quad \ldots \ldots \quad (16)$$

where e/D is the relative roughness and A is a constant. A plot of the experimental values of $[(r/V)\ dV/dr + 1]\ B/r$ versus D is shown as Figure 5. Also shown is a line with a slope of - 1/4, corresponding to (16).

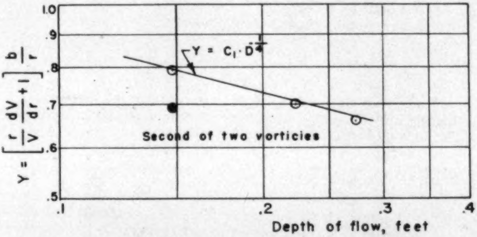

Fig. 5--Experimental values of $[(r/V)\ dV/dr + 1]\ B/r$ plotted against depth for a hydraulically rough channel

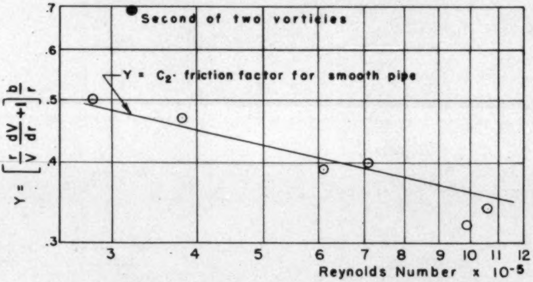

Fig. 6--Experimental values of $[(r/V)\ dV/dr + 1]\ B/r$ plotted against Reynolds number for a hydraulically smooth channel

For the smooth channel (Fig. 6), the friction factor should be proportional to the Reynolds number. Accordingly, $[(r/V)\ dV/dr + 1]\ B/r$ has been plotted against the Reynolds number, based on mean velocity and hydraulic radius. In the same plot is shown a line proportional to the friction factor for pipes having the same hydraulic radius and Reynolds number.

Effect of the width-depth ratio--As previously noted, (15) applies only to the central portions of the main vortex. As the width available for this vortex increases, however, the boundary layer grows in thickness towards the surface, and friction begins to affect the surface layer. Eq. (14)

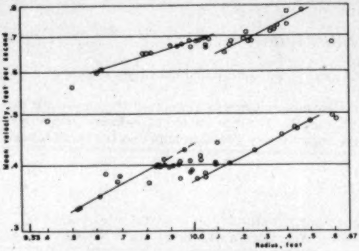

Fig. 7--Velocity distribution in a wide shallow bend; upper: smooth bed, depth 0.11 ft; lower: rough bed, depth 0.15 ft

predicts that the radial velocity gradient will decrease, approaching zero as the friction slope approaches the surface slope. This phenomenon was observed in those runs made at shallow depths, as shown in Figure 7 for both smooth and rough bottom conditions. However, curvilinear flow with a zero radial velocity gradient seems also to be unstable, for a new boundary layer with a second circulation vortex forms to occupy the rest of the channel width.

The onset of the double vortex pattern is affected by the friction factor; for the hydraulically rough channel it appeared at a width-depth ratio of 9, whereas in the smooth channel it appeared at a ratio of about 12. Since the rate of boundary layer growth is dependent on the friction factor, this is the trend to be expected.

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IMPROVED MODELS OF THERMAL DIFFUSION IN THE SOIL

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Abstract--It is shown that the non-homogeneous case of soil-heat conduction, that is, when soil-heat conductivity and capacity are functions of depth, can be treated rigorously. An exact formula is derived which gives the thermal diffusivity of the soil as a function of depth, on the basis of Fourier coefficients of diurnal courses of soil temperature at a variety of depths. By employment of the new model of soil-heat diffusion one avoids misleading results which are obtained when the classical model of heat diffusion in a solid conductor is applied to natural soil indiscriminately.

The case of depth-time varying thermal diffusivity can only be solved in approximate form. The practical application of the classical and the two new models is discussed with the aid of soil-temperature data obtained by the Johns Hopkins Laboratory of Climatology, Seabrook, N. J.

Introduction--The classic method of soil-temperature analysis is based on the prototype of heat diffusion in a semi-infinite solid conductor, when harmonically varying boundary conditions (usually in the form of surface-temperature oscillations) are externally forced upon the system in which the two characteristic heat parameters (that is, heat conductivity and heat capacity) are not functions of either one of the independent variables, depth z and time t. Quite often, the results of a Fourier analysis of actual subsoil-temperature variations (harmonical, or quasi-harmonical) contrast markedly to predictions based on the classical model. The best-known example is that any of the harmonics of diurnal or annual temperature oscillations fail to obey the law of the classical theory which states that the phase retardation per unit depth be constant and equal to the rate at which the natural logarithm of amplitude decreases per unit depth.

An obvious reason for such failure derives from the inhomogeneity of natural soil. Density, porosity, moisture content, and other factors are usually functions of depth. Recently, DE VRIES [1952] has thoroughly discussed the available information in regard to dependency of heat conductivity and capacity of the soil on variations of the above factors, especially soil-moisture content. De Vries' theoretical and experimental results confirm the findings of various authors inasmuch as heat conductivity and capacity may vary up to one order of magnitude within soil layers of a few centimenters thickness.

During periods of clear weather the soil dries out, and the rate of soil-water evaporation at the surface is a function of the temperature, among other factors. As a direct consequence, we can expect diurnal variations of soil moisture. Therefore, heat conductivity and capacity of natural soil will be functions of the time of the day in addition to being functions of depth. Thus, another reason for the failure of the classical model becomes obvious, namely, the assumption that at a given level the heat parameters are independent of time.

When, as is customary, only observations of soil temperature in a depth-time frame are available, we are primarily interested only in the ratio of heat conductivity to heat capacity, which defines the thermal diffusivity. Since heat conductivity and capacity have significantly different responses to soil-moisture variations, the thermal diffusivity of natural soil will not satisfy the requirements of homogeneity and constancy of the classical model in all cases where a z and t dependency of soil moisture exists.

The above thoughts are elementary and self-suggestive, and certainly not new. However, to the best of the author's knowledge, there is no simple method other than the oversimplified classical model which describes thermal diffusion in natural soil. It will be shown that one can readily discard the assumption of vertically homogeneous thermal diffusivity. One can obtain straightforwardly and exactly the depth-varying thermal diffusivity from the Fourier coefficients of time series of temperature at a variety of depths. However, when in addition to the z-dependency the thermal diffusivity has also a t-dependency, cumbersome mathematics are involved in the theoretical analysis. Without any additional information other than temperature observations in a time-depth frame, we can obtain only approximate expressions of the thermal diffusivity.

Explanation of symbols--The two independent variables are t = time, sec, and z = depth below the soil surface, cm. The dependent variables are T = soil temperature, °C, and B = vertical heat flux = sensible heat conducted in the z direction at depth z, cal cm^{-2} sec^{-1}. The heat parameters of the soil are λ = heat conductivity at depth z, cal cm^{-1} sec^{-1} $(°C)^{-1}$, and C = heat capacity per unit volume at depth z, cal cm^{-3} $(°C)^{-1}$. The ratio $\lambda/C = \kappa$ = thermal diffusivity at depth z, cm^2 sec^{-1}.

The following terms of Fourier series are used: ν = frequency of the diurnal oscillation = 0.0000729 sec^{-1}; n = integer denoting the wave number or order of a harmonic, n = 1, 2, 3, . . .; a, b, $\Delta\lambda$, and ΔC = amplitudes; $\alpha, \beta, \delta, \epsilon, \psi$, and ϕ = phase angles. The subscript n refers the value of an amplitude or a phase angle to the nth harmonic. The subscript m refers the value of a dependent variable or a parameter to a 24-hourly average. Throughout the paper the Fourier series is given the form $a_n \cos(n\nu t - \alpha_n)$, etc. In comparison with the more conventional form employing the sine function and a positive phase angle, the form used here has the advantage that $\alpha_n/n\nu$ produces directly the time of the maximum value of the nth harmonic.

MacLaurin's series is given in a form where z_i = level of soil-temperature observation, cm, and Y = function of z.

The following mathematical symbols are used: The prime (′) denotes partial differentiation with respect to z, for example, $T'' = \partial^2 T/\partial z^2$; the dot (˙) denotes partial differentiation with respect to t, for example, $T'^{\cdot} = \partial(\partial T/\partial z)/\partial t$; the bar (¯) denotes that a value is independent of time. The double bar (=) denotes that a value is independent of both time and depth, and $\log_e$ = natural, or Naperian logarithm.

Physical and mathematical relations--The two fundamental equations are the equation of heat conduction

$$B = -\lambda T' \quad \ldots\ldots (1)$$

and the equation of heat continuity

$$B' = -C\,T^{\cdot} \quad \ldots\ldots (2)$$

To apply (1) to soil conditions we must assume that vertical advection of heat is absent; this excludes seepage of soil water or other mass movements. Then, (1) is the equation of definition of $\lambda = -B/T'$. To apply (2) to soil conditions we must assume that horizontal components of heat conduction are non-existent or at least non-divergent, and that no heat sources or sinks occur at any depth except at the surface; this excludes any phase transformation of soil H_2O, or any heat consuming or producing chemico-physical reactions, with the exception of evaporation, condensation, sublimation, etc., at z = 0. Then, (2) is the equation of definition of $C = -B'/T^{\cdot}$.

It is always possible to express the temporal variations of soil temperature at any depth by means of a Fourier series

$$T = T_m + t\,T_m^{\cdot} + \sum_n a_n \cos(n\nu t - \alpha_n) \qquad n = 1, 2, 3, \ldots \quad \ldots\ldots (3)$$

To improve the degree of approximation, a linear trend is considered in (3). All coefficients T_m, $T_m^{\cdot}$, a_n, and α_n are functions of z, and independent of t during the time interval from t_o to $t_o + 1/\nu$. Upon differentiating (3) once with respect to t

$$T^{\cdot} = T_m^{\cdot} - \nu \sum_n n\,a_n \sin(n\nu t - \alpha_n) \quad \ldots\ldots (4)$$

Examples of Fourier coefficients at a variety of discrete depths are listed in Table 1. These data are based on one of the sets of observations obtained by the Laboratory of Climatology of the Johns Hopkins University, Seabrook, N. J. The test site at Shirley, N. J., was a large flat bare field so that horizontal uniformity of geophysical conditions can be assumed. In addition to soil temperature, hourly observations of a great variety of meteorological factors are elaborated with a thoroughness and accuracy which compares favorably to that customary in experimental physics [SEABROOK REPORT, 1952]. Therefore, it appears justifiable to analyze the observational data of individual days more thoroughly than customary in previous papers.

It is convenient to express the z-dependency of the Fourier coefficients in terms of MacLaurin's series. When the value of a quantity $\overline{Y}$ is given at i equidistant observation levels, we introduce the mean depth Z

Table 1--Examples of results of Fourier analysis based on hourly soil-temperature observations at indicated depths, z_i, Shirley, N. J., April 17, 1952, 00h 00m to 24h 00m EST, T_m = 24 hourly average, $T_m^{\cdot}$ = mean trend (midnight difference), a_1 to a_3 = amplitudes, α_1 to α_3 = phase constants of the first three harmonics[a]

z_i	T_m	$T_m^{\cdot}$	a_1	a_2	a_3	α_1	α_2	α_3
cm	°C	°C/24 hr	°C	°C	°C	deg	deg	deg
2.5	13.04	3.20	8.51	2.72	0.61	202.9	7.6	82.8
5.0	12.63	2.87	6.67	2.02	0.45	217.2	28.8	109.5
7.5	12.26	2.57	5.53	1.60	0.41	224.5	40.7	123.3
10.0	11.91	2.42	4.51	1.30	0.19	236.9	54.6	136.4

[a] The Fourier analysis was applied after the mean trend correction was added to the raw data.

Table 2--Constants of MacLaurin's series (7a) which produce best-fitting numerical expressions of the depth variation of the Fourier coefficients listed in Table 1

$\overline{Y}$	$\overline{\overline{Y}}$	$\overline{\overline{Y'}}$	$\overline{\overline{Y''}}$	Units of $\overline{Y}$
$\log_e T_m$	2.521	-0.012	0.0001	number
$\dot{T}_m$	2.701	-0.106	0.0164	°C/24 hr
$\log_e a_1$	1.802	-0.084	0.0030	number
$\log_e a_2$	0.637	-0.098	-0.0072	number
$\log_e a_3$	-0.816	-0.143	-0.0370	number
α_1	221.0	4.37	-0.16	deg
α_2	35.2	6.12	-0.57	deg
α_3	117.2	6.99	-1.09	deg

$$Z = (1/i) \sum_i z_i \quad \ldots\ldots\ldots \quad (5)$$

and write

$$\overline{Y}_i = \overline{\overline{Y}} + \overline{\overline{Y'}}(z_i - Z) + \overline{\overline{Y''}}(z_i - Z)^2/2 + \ldots \quad \ldots (6)$$

A total number of i coefficients $\overline{\overline{Y}}$, $\overline{\overline{Y'}}$, $\overline{\overline{Y''}}$, ..., can be derived by the method of least squares. For practical computations a total of three coefficients will normally be sufficient when, in view of the known results of the classical model of heat diffusion, one expands α_n, and $\log_e a_n$ rather than a_n. Examples are listed in Table 2. When (6) is written in the form $\overline{Y} = f(z)$

$$\overline{Y} = \overline{\overline{Y}} + \overline{\overline{Y'}}(z - Z) + \overline{\overline{Y''}}(z - Z)^2/2 \ldots \quad (7a)$$

we obtain

$$(\overline{Y})' = \overline{\overline{Y'}} + \overline{\overline{Y''}}(z - Z) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7b)$$

and

$$(\overline{Y})'' = \overline{\overline{Y''}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7c)$$

In the case that Y equals $\log_e a$ one must consider in (7b and c) that $Y' = a'/a$, and $Y'' = a''/a - (a'/a)^2$. Thus, (7a,b,c) represent convenient interpolation formulas for any order derivatives with respect to z. For suitably chosen observation depths these equations can be used for extrapolation purposes, too; for example, the Shirley data permit extrapolation to the soil surface, z = 0.

After having evaluated the coefficients of the Fourier and MacLaurin series it is a matter of elementary mathematics to obtain from (3) expressions like

$$T' = T_m' + t\, T_m^{\cdot\,\prime} + \sum_n \left[a_n' \cos(n\nu t - \alpha_n) + a_n \alpha_n' \sin(n\nu t - \alpha_n)\right] \quad \ldots\ldots \quad (8)$$

and to evaluate the derivatives T′, T″, . . ., numerically at any time t and any depth z within the limits of the depth-time frame of soil-temperature observations and possible extrapolations, by what one might call a Fourier Synthesis. Summarized, the above procedures represent a numerically exhaustive, yet still descriptive analysis of the observational data. In Figure 1 we have illustrated a result of such analysis for the set of 24-hourly soil-temperature observations at the Johns Hopkins Laboratory of Climatology obtained on May 1, 1952.

To proceed further towards a theoretical analysis we assume that our other dependent variable, which is the heat flux B, follows from a Fourier series similar to that of T, as given by (3)

$$B = B_m + t\,B_m^{\cdot} + \sum_n b_n \cos(n\nu t - \beta_n) \qquad n = 1, 2, 3, \ldots \qquad (9)$$

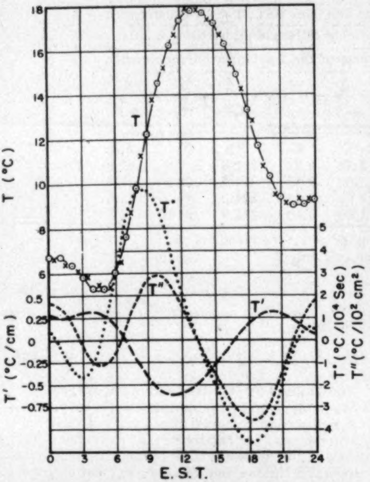

Fig. 1--Example of a diurnal course of soil-temperature T, Shirley, N. J., May 1, 1952, 2.5 cm below the surface of a bare field; the crosses denote T values observed at 30 min after each hour, the circles denote computed T values at the hour, computed by superposition of 24-hourly mean, mean trend, and first three harmonics of the diurnal variation; the first-order partial derivatives with respect to time and depth ($T^{\cdot}$ and T') and the second-order derivative with respect to depth (T'') are obtained by means of a MacLaurin expansion of the Fourier coefficients; the derivatives are valid for the depth of $z = 2.5$ cm

where all coefficients B_m, $B_m^{\cdot}$, b_n, and β_n are functions of z.

No problem whatsoever would exist when, in addition to soil-temperature observations, a complete set of heat-flux observations in a depth-time frame would be available. Then, (1) and (2), and subsequent relations such as (3), (4), (8), together with (9) and one similar to (8) in terms of B', would result in numerical values of λ and C at any t and any z. However, direct heat-flux measurements are more complicated than temperature observations. Usually, the heat flux must be considered the unknown quantity to be evaluated from soil-temperature observations. The conventional approach is to derive the thermal diffusivity by using a theoretical model of the soil-temperature variations; to add independent information regarding the heat capacity of the soil; then, to estimate λ on the basis of κ and C values; and finally, to obtain the heat flux with the aid of (1).

The difficulties of this procedure lie in the facts outlined previously, that is, that the heat parameters of natural soil are never constant and that only the classical model was available which over-simplifies the theoretical approach. In full acknowledgement of the first fact we must write

$$\lambda = \lambda_m + t\,\lambda_m^{\cdot} + \sum_n \Delta\lambda_n \cos(n\nu t - \psi_n) \ldots (10)$$

$$C = C_m + t\,C_m^{\cdot} + \sum_n \Delta C_n \cos(n\nu t - \phi_n) \ldots (11)$$

where the coefficients of these Fourier series are functions of depth. With regard to the second fact we note that the classical model is characterized by the requirements $\lambda^{\cdot} = \lambda' = 0$, and $C^{\cdot} = C' = 0$. We shall discuss two new models of thermal diffusion by gradually discarding some of the restrictive requirements of the classical theory. The first new model is characterized by the requirements $\lambda^{\cdot} = C^{\cdot} = 0$, while $\lambda = \overline{\lambda}$ and $C = \overline{C}$ can be arbitrary functions of depth. In the second model a specialized form of temporal variations of C is considered, in addition to λ and C being unrestricted functions of depth.

Model of thermal diffusion for depth-varying heat parameters--Although the coefficients of the B series (9) are unknown, we can assume that the series exists. We differentiate (9) once with respect to z

$$B' = B_m' + t\,B_m^{\cdot\prime} + \sum_n [b_n' \cos(n\nu t - \beta_n) + b_n\beta_n' \sin(n\nu t - \beta_n)] \ldots\ldots (12)$$

In view of (8) and (12), and (1) and (2) we define two convenient abbreviations in form of the angular functions of depth ϵ_n and δ_n

$$\tan \epsilon_n = -\alpha_n'/(\log_e a_n)' \ldots\ldots (13)$$

$$\tan \delta_n = -(\log_e b_n)'/\beta_n' \ldots\ldots (14)$$

With the aid of (13) and (14) we can rewrite (8) and (12) as follows

$$T' = T_m' + t\,T_m^{\cdot\prime} - \sum_n (a_n \alpha_n'/\sin \epsilon_n) \cos (n\nu t - \alpha_n + \epsilon_n) \quad (15)$$

$$B' = B_m' + t\,B_m^{\cdot\prime} + \sum_n (b_n \beta_n'/\cos \delta_n) \sin (n\nu t - \beta_n - \delta_n) \quad (16)$$

A comparison of (15) with (3) shows that ϵ_n is the phase difference between T′ and T waves. Upon introducing series (9) and (15) into (1), a comparison of corresponding terms yields

$$B_m = -\bar{\lambda}\,T_m' \qquad B_m^{\cdot} = -\bar{\lambda}\,T_m^{\cdot\prime} \quad (17)$$

$$\beta_n = \alpha_n - \epsilon_n \quad (18)$$

$$b_n = \bar{\lambda}\,a_n \alpha_n'/\sin \epsilon_n \quad (19)$$

Temperature observations in a depth-time frame and a descriptive analysis discussed previously produce straightforwardly the numerical values of ϵ_n in (13). Therefore, we can determine the numerical values of β_n with the aid of (18). This equation illustrates another physical meaning of ϵ_n inasmuch as $\epsilon_n/n\nu$ is the time difference between the occurrence of maximum phase of temperature and heat-flux waves for the nth harmonic, if $\lambda = \bar{\lambda}$, that is, λ is independent of time.

Upon introducing series (4) and (16) into (2), a comparison of corresponding terms yields

$$B_m' = -\bar{C}\,T_m^{\cdot} \qquad B_m^{\cdot\prime} = 0 \quad (20)$$

(This zero value follows from the assumed linearity of the temperature trend.)

$$\beta_n + \delta_n = \alpha_n \quad (21)$$

$$n\nu\,a_n\,\bar{C} = b_n \beta_n'/\cos \delta_n \quad (22)$$

In contrast to ϵ_n, the quantity δ_n as defined in (14) is not directly determinable as long as the coefficients b_n of the B series (9) are unknown. However, because (21) and (18) hold true simultaneously

$$\delta_n = \epsilon_n \quad (23)$$

Finally, we divide (22) by (19) and solve for $\bar{\lambda}/\bar{C}$, and consider (23)

$$\bar{\lambda}/\bar{C} = \bar{\kappa} = (n\nu \sin \epsilon_n \cos \epsilon_n)/(\alpha_n' \beta_n') = (n\nu \sin 2\epsilon_n)/(2\alpha_n' \beta_n') \quad (24)$$

Eq. (24) produces the thermal diffusivity $\bar{\kappa}$ in terms of experimental data derived from a depth-time frame of soil-temperature observations; it is an exact equation even though $\bar{\lambda}$ and $\bar{C}$, and therefore $\bar{\kappa}$ may depend on depth z in any manner.

Table 3--Examples of ϵ_n = phase lag between temperature and temperature gradient waves, and β_n' = first derivative with respect to depth of β_n = phase constant of heat-flux waves; n = order of harmonic; the values were computed from the data in Tables 1 and 2 under the assumption that $\lambda = \bar{\lambda}$ and $C = \bar{C}$

z	ϵ_1	ϵ_2	ϵ_3	β_1'	β_2'	β_3'
cm	deg	deg	deg	rad/cm	rad/cm	rad/cm
0.0[a]	42.5	72.6	110.3	0.0948	0.2293	0.4450
2.5	42.4	63.8	89.1	0.0874	0.2125	0.3874
5.0	42.3	53.3	56.3	0.0801	0.1958	0.3281
7.5	42.3	41.3	27.5	0.0728	0.1790	0.2687
10.0	42.3	29.0	10.2	0.0654	0.1623	0.2111

[a] Extrapolated with the aid of MacLaurin's series.

In Table 3 we have listed examples of ϵ_n and β_n' values as computed from the data given in Tables 1 and 2. The last step of the theoretical analysis would require independently observed $\overline{C}$ values in order to obtain $\overline{\lambda} = \kappa \overline{C}$, whereupon the totality of the unknown coefficients of the heat-flux series (9) are produced with the aid of (19) and (17).

One can readily verify that the classical model is a special case of the new model, namely, only when $\alpha_n' = \beta_n'$ (that is, when in (18), $\epsilon_n' = 0$, or $\epsilon_n = \bar{\epsilon}_n = \text{const}$), and furthermore, when $\bar{\epsilon}_n = 45°$ (that is, $\sin \epsilon_n = \cos \epsilon_n$ or $\tan \epsilon_n = 1$), we find that $\bar{\kappa}$ equals the constant $= \bar{\bar{\kappa}}$, while (13) and (24) yield

$$\alpha_n' = -(\log_e a_n)' = \sqrt{n\nu/(2\bar{\bar{\kappa}})} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(25)}$$

The well-known laws of the classical theory follow directly from above. For example, $\epsilon_n = 45°$ in (18) expresses the fact that, at any depth, the harmonics of order n of temperature lag 45° behind the same harmonic of heat-flux. Relation (25) indicates that, for the nth harmonic, the phase retardation per unit depth difference is constant and equal to the rate at which the natural logarithm of amplitude decreases with depth, that is, equal to the amplitude decrement. Furthermore, the phase retardations of two different harmonics follow the ratio $\alpha_{n+i}'/\alpha_n' = \sqrt{(n+i)/n}$; the same ratio controls the relative amplitude decrement or, inversely, the penetration depths.

Table 4--Examples of computed thermal diffusivity from properties of the second harmonic (12-hourly wave) of soil-temperature variations at Shirley, N. J., April 17, 1952, at indicated depths

z	Classical model		New model I $\bar{\kappa}_2$
	Fictitious $\bar{\bar{\kappa}}_2$ from phase lag	Ficititious $\bar{\bar{\kappa}}_2$ from amplitude decrement	
cm	cm^2/sec	cm^2/sec	cm^2/sec
0.0[a]	0.0025	0.0259	0.0011
2.5	0.0035	0.0144	0.0019
5.0	0.0051	0.0092	0.0030
7.5	0.0082	0.0068	0.0043
10.0	0.0152	0.0047	0.0055

[a] Extrapolated with the aid of MacLaurin's series.

Applying the data listed in Tables 1 to 3 to the classical model can produce embarrassing results. This is exemplified in Table 4. One can find that a fictitious thermal diffusivity computed from the observed phase lags differs by one order of magnitude from that derived by means of the amplitude decrements. Furthermore, both "diffusivities" exhibit an apparent dependency on depth, yet of opposite sign. Similar results have been reported by various authors. As an example, we mention the investigations of soil-temperature waves by WÄCHTERSHÄUSER [1951]. We also can refer to the suggestion by ANDERKO [1913] to utilize such discrepancies as a descriptive measure of non-homogeneity of the soil, even though Anderko, erroneously, saw in these facts an outgrowth of "pseudo-isotropy" of soil-heat parameters.

Any discussion of the apparent depth dependency of $\bar{\bar{\kappa}}$ values is illogical because the formulas of the classical model cease to be valid for an inhomogeneous conductor. When the analysis of soil-temperature observations results in different $\bar{\bar{\kappa}}$ values at different levels, the proper step to be taken is to consider the classical model inadequate for the case under investigation. We can legitimately reverse the sequence of conclusions by saying that different rates of depth variation of α_n and $\log_e a_n$, for a fixed n value, prove the existence of inhomogeneity of thermal diffusivity along the vertical coordinate. A physically sound measure of such inhomogeneity is $\bar{\kappa} = f(z)$ in formula (24). An example of practical application of (24) is shown in Table 4.

Usually, the classical model is derived from properties of a particular solution of the second-order differential equation of thermal diffusion. One obtains this equation by differentiation of (1) once with respect to z upon elimination of B' with the aid of (2) after solving for $T^{\cdot}$

$$T^{\cdot} = T'' \lambda / C + T' \lambda'/C \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(26)}$$

which, in the case of $\lambda' = 0$ reduces to

$$T^{\cdot} = T'' \lambda / C \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(27)}$$

When, in addition, $C' = 0$, the partial differential equation of second-order $T^{\cdot} = \bar{\bar{\kappa}} T''$ can readily be solved. It is much more difficult to integrate (26). The necessary requirement of the integration is an a priori knowledge of the analytical forms $\overline{\lambda} = f(z)$ and $\overline{C} = f(z)$. Only for a few very special cases of such analytical forms is it possible to express T in (26) by known, that is, tabulated functions.

Our approach avoids the need for solving the second-order differential equation (26). We have considered that (26), although B has been eliminated, is not independent of the simultaneous B equation. One obtains the partial differential equation for B by differentiation of (1) once with respect to t and of (2) once with respect to z. After eliminating $\dot{T}'$, and solving for $\dot{B}$

$$\dot{B} = B'' \lambda/C + B\,\dot{\lambda}/\lambda - B'\,C'\,\lambda/C^2 \quad \ldots\ldots\ldots\ldots (28)$$

In the case of $C' = \dot{\lambda} = 0$

$$\dot{B} = B'' \lambda/C \quad \ldots\ldots\ldots\ldots (29)$$

In view of these equations we started out with the legitimate assumption that a solution of either form of the B equation exists and is expressed by series (9) just as, simultaneously, a corresponding solution of the T equation exists and is expressed by series (3).

When inhomogeneity of thermal diffusivity along the vertical coordinate is the sole cause of the failure of the classical model, the relations of the new model as derived above would be sufficient for the theoretical analysis of soil-temperature observations. In reality, Table 5 reveals the disturbing fact that (24) results in $\bar{\kappa}_n$ values which depend significantly on the order n of the harmonic employed for computation. Nevertheless, Table 5 evidences the noteworthy feature that

Table 5--Examples of computed thermal diffusivity $\bar{\kappa}_n$ on the basis of (24) for the first, second, and third harmonic of soil-temperature variations at Shirley, N. J., April 17, 1952, at indicated depths

z	$\bar{\kappa}_1$ (24 hourly wave)	$\bar{\kappa}_2$ (12-hourly wave)	$\bar{\kappa}_3$ (8-hourly wave)
cm	cm^2/sec	cm^2/sec	cm^2/sec
0.0[a]	0.0041	0.0011	-0.0007
2.5	0.0048	0.0019	0.0001
5.0	0.0057	0.0030	0.0021
7.5	0.0068	0.0043	0.0034
10.0	0.0084	0.0055	0.0035

[a] Extrapolated with the aid of MacLaurin's series.

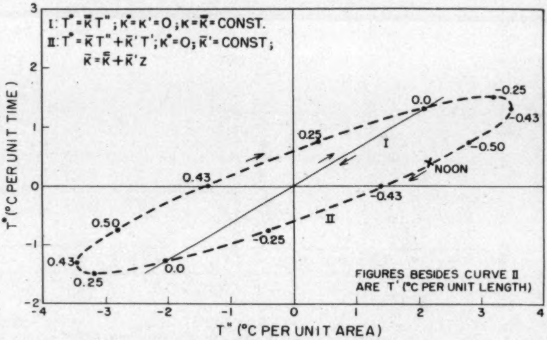

Fig. 2--Schematic relations between partial derivatives of soil temperature at a fixed depth in the $\dot{T}$ - T'' diagram the depth dependency of the $\bar{\kappa}_n$ values is nearly the same. That is to say, the differences $\bar{\kappa}_1 - \bar{\kappa}_2$ and $\bar{\kappa}_1 - \bar{\kappa}_3$ are approximately independent of depth, even though the absolute values are affected by the variation of n so that one of the $\bar{\kappa}_3$ values turns out to be negative!

We can formulate a statement similar to that made before: Differences of $\bar{\kappa}_n$ computed with the aid of (24) for different n values (for a fixed value of z) prove that the true thermal diffusivity at depth z is a harmonic or quasi-harmonic function of time during the investigation interval from t_o to $t_o + 1/\nu$. To substantiate this we refer to the results of a descriptive analysis of soil-temperature observations illustrated in Figure 1. As evidenced by the form of (27), the observed $T^{\cdot}$ and T'' values should follow an exact linear relationship if the soil-heat parameters satisfy the requirements of the classical model. If, at a given depth z, we would have $\lambda' \neq 0$, yet $\lambda'/C = \text{const}$, (26) indicates that the observed $T^{\cdot}$ and T'' should follow a relationship as illustrated schematically in Figure 2, namely, for an existing T' and λ being independent of time, the straight lines of the $T^{\cdot}$ versus T'' diagram would appear simply displaced parallel to themselves, so that a harmonically oscillating T' function produces the ellipse. In reality, the relationship between $T^{\cdot}$ and T'' is more complicated than in either one of the two schemes of Figure 2. With the aid of the Fourier and MacLaurin expansions of actual data we found the result illustrated in Figure 3.

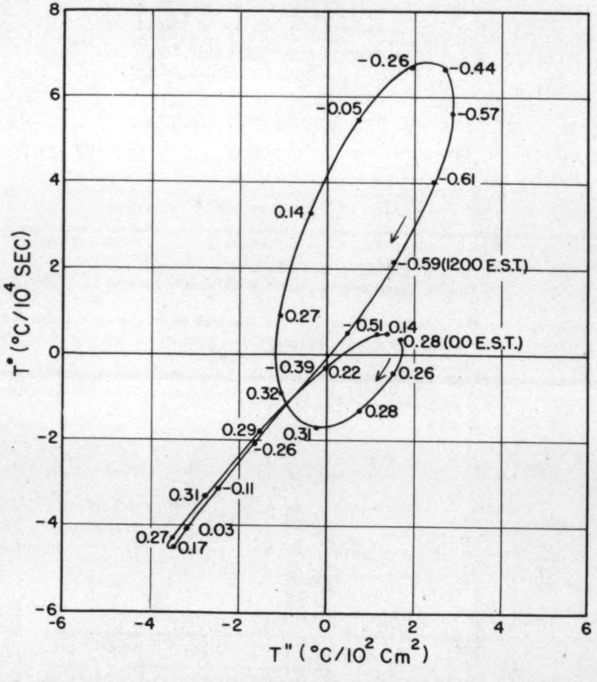

Fig. 3--Observed relation between partial derivatives of soil temperature at the depth of z = 2.5 cm in the $T^{\cdot}$ - T'' diagram, Shirley, N. J., May, 1952; the numbers beside the curve connecting the coherent $T^{\cdot}$ and T'' values denote T' values, °C/cm; the beginning (at 00h 00m EST) and middle (12h 00m EST) of the diurnal course is also marked

In view of the known dependency of λ, C, and λ/C on the soil-moisture content one might expect that Figure 3 indicates more or less directly the variations of moisture in the soil at the reference level. However, one must consider also the possibility that soil-water movements can disturb the process of genuine conduction of heat, so that owing to advection processes (1) does not describe truly the distribution and diffusion of heat. Furthermore, the transfer of water vapor from layer to layer in the soil and the evaporation and condensation of very small amounts of water could absorb and liberate sufficient latent heat to mask significantly the continuity condition of heat as given by (2). The latter point has been emphasized by SWINBANK [1948]. Summarized, the need for further extension of the model of soil-heat diffusion becomes obvious.

Model of thermal diffusion for depth-time varying heat parameters--Series (10) and (11) permit us to account fully for any possible depth-time dependency of the heat parameters. The number of unknowns thus introduced is 2 (2n + 2), which must be considered in addition to the (2n + 2) unknowns of Series (9) and the (2n + 2) unknowns of Series (12), so that the total number of unknowns is 4 (2n + 2). There are only 2 (2n + 2) equations at our disposal, namely, (1) for the 2n + 2 terms of Series (15), and (2) for the 2n + 2 terms of Series (4). Thus, it appears impossible to solve the system if no additional information is provided.

Now, we found that, not only the 2 (2n + 2) coefficients of Series (9) and (12), but also n values of $\bar{\kappa}_n$ were obtained. This could be achieved because a group of n of the above equations had produced directly the n values of β_n at a variety of depths, so that the n unknowns β_n' could be evaluated independently and directly by differentiation of the series for β_n. Closer inspection shows that such direct evaluation of β_n' is possible only when (10) reduces to

$$\lambda = \bar{\lambda} = \text{independent of time} \quad \dots\dots\dots\dots\dots\dots\dots \quad (30)$$

yet $\bar{\lambda}$ = unrestricted function of depth. A direct consequence of $\lambda^{\cdot} = 0$ is that (28) becomes similar to (26).

In practical cases of soil-temperature analysis the number of harmonics n can hardly be chosen greater than three. Therefore, the three unknowns which possibly can be determined in a system which is based on the validity of equations (1) and (2) are either $\bar{\kappa}_1$, $\bar{\kappa}_2$, $\bar{\kappa}_3$, as in the above new Model I, or, in view of (10), (11), and (30), the three coefficients $\bar{\lambda}/C_m$, $\Delta C_1/C_m$, and ϕ_1. Then, a new Model II is characterized by the assumption that condition (30) holds true, and that the thermal diffusivity follows

$$\kappa^{-1} = C/\bar{\lambda} = (C_m/\bar{\lambda})\,[1 + (\Delta C/C_m)\cos(\nu t - \phi)] \quad \dots\dots\dots\dots \quad (31)$$

where, for brevity, $\Delta C/C_m$ and ϕ is written instead of $\Delta C_1/C_m$ and ϕ_1. The new Model II, although allowing for unrestricted depth variation of $\bar{\lambda}$ and C, imposes severe restrictions as regards the time variation of the soil-heat parameters, inasmuch as only the first order harmonic of a C variation can possible be considered.

The development of the analytical relations of this model involves rather lengthy yet elementary transformations. We begin with (2) and consider (11) and (31), whereupon

$$B' = -\,[C_m + \Delta C\cos(\nu t - \phi)]\,[T_m^{\cdot} - \nu\sum_n n a_n \sin(n\nu t - \alpha_n)] \quad \dots\dots\dots\dots \quad (32)$$

The following general relation of the theory of harmonic functions can be used

$$\sin[(x + y)/2]\cos[(x - y)/2] = (\sin x + \sin y)/2 \quad \dots\dots\dots\dots\dots\dots \quad (33)$$

which gives, in view of (32)

$$2\sin(n\nu t - \alpha_n)\cos(\nu t - \phi) = \sin[(n + 1)\,\nu t - \alpha_n - \phi] + \sin[(n - 1)\,\nu t - \alpha_n + \phi] \quad \dots\dots \quad (34)$$

With the aid of (34), (32), and several of the relations of Model I we obtain, finally, the following three equations for the three unknowns as given by (31)

$$\bar{\lambda}/(C_m\,\bar{\kappa}_1) = 1 + [(T_m^{\cdot}/\nu)\sin(\beta_1 - \phi) + a_2\cos(\alpha_2 - \beta_1 - \phi)]\,\Delta C/(C_m\,a_1\cos\epsilon_1) \quad \dots\dots \quad (35)$$

$$\bar{\lambda}/(C_m\,\bar{\kappa}_2) = 1 + [3a_3\cos(\alpha_3 - \beta_2 - \phi) + a_1\cos(\alpha_1 - \beta_2 + \phi)]\,\Delta C/(4C_m\,a_2\cos\epsilon_2) \quad \dots\dots \quad (36)$$

$$\overline{\lambda}/(C_m \overline{\kappa}_3) = 1 + [3a_2 \cos(\alpha_2 - \beta_3 + \phi)]\, \Delta C/(3C_m a_3 \cos \epsilon_3) \ldots\ldots\ldots (37)$$

where $\overline{\kappa}_n$ is given by the right-hand side of (24) for n = 1, 2, and 3.

We have computed $\overline{\lambda}/C_m$, $\Delta C/C_m$, and ϕ on the basis of the observational data listed in Tables 1, 3, and 5. The results are presented in Table 6. The comparison of $\overline{\lambda}/C_m$ with the $\overline{\kappa}_n$ values listed in Table 5 shows that the depth dependency indicated by the values of Table 5 is approximately confirmed, while the "improved" (or truly representative 24-hour average) values of $\overline{\lambda}/C_m$ lie between $\overline{\kappa}_1$ and $\overline{\kappa}_2$. The phase constants ϕ indicate that the maximum phase of the assumed C variation occurs shortly after midnight at z = 0, or the minimum phase occurs shortly after noon, since 8.6° correspond to 00h 34m EST. This appears correct because the soil near the surface will be driest shortly after noon. The indicated lagging with increasing depth also appears very reasonable. However, the relative amplitudes $\Delta C/C_m$ are obviously too large. PORTMAN [1951] has assumed that the soil near Shirley, N. J., has a heat capacity per unit volume which can be described by C = 0.20 + 0.80 w, or C = 0.20 + W, when w = fraction of water (by weight) of a moist sample, or W = mass of water (grams) per cm³. Even though one might assume a rather excessive diurnal variation of W in the soil layer near the surface, one cannot tolerate $\Delta C/C_m$ values of more than approximately 0.4. Obviously, the unrealistic $\Delta C/C_m$ values of Table 6 result from the oversimplification as regards the form of possible temporal variations of the heat parameters, especially the neglect of λ variations, which certainly exist and accompany the C variations produced by changes of W. We also can refer to the points discussed at the end of the preceding section.

Table 6--Characteristic data of soil-heat parameters when $\lambda' = 0$ and $C = C_m + \Delta C \cos(\nu t - \phi)$; the computation is based on Model II and the properties of the first, second, and third harmonic of the diurnal course of soil temperature at Shirley, N. J., April 17, 1952

z	$\overline{\lambda}/C_m$	$\Delta C/C_m$	ϕ
cm	cm²/sec		deg
0.0	0.0023	1.31	8.6
2.5	0.0032	0.98	28.6
5.0	0.0047	0.52	43.9
7.5	0.0059	0.42	48.4
10.0	0.0072	0.52	54.4

Conclusions and recommendations--It is noteworthy that a possible time dependency of the soil-heat parameters affects the various harmonics of the soil-temperature variations differently. As a direct consequence it can be said, that high-order harmonics of temperature can be produced. To substantiate this, we can assume that in an idealization of realistic cases, the boundary conditions of heat flux at the interface are exactly and uniquely described by a 24-hourly B wave, which follows from idealized courses of solar and atmospheric radiation processes. Suppose that the energy release at the interface produces also a 24-hourly wave of evaporation. The B wave is accompanied by a 24-hourly T wave, the evaporation wave by one of soil moisture, which causes the heat parameters (for example, $1/\lambda$) to show a 24-hourly variation. Eq. (1) and a development along the lines of relations (32) and (34) prove directly that T′ must exhibit not only a 24-hourly but also a 12-hourly wave. Since the integration of T′ with respect to z does not affect the time dependency, soil temperature itself must show both a 24- and 12-hourly wave. Consequently, it is legitimate to say that high-order harmonics of soil-temperature oscillations can be produced internally, without being explicitly predescribed by the external or boundary conditions. In real cases, a rather complicated interaction of internal and external processes will exist.

It may be mentioned that the above discussed mechanism of producing high-order harmonics is likely to be important in the atmosphere near the ground. A relatively strong and straightforward relationship between eddy thermal conductivity and the vertical gradient of temperature exists here. A discussion of the consequences of the above nature appears interesting inasmuch as a number of meteorological elements possess surprisingly regular 12-, 8-, and even 6-hourly waves, while the primary forcing functions are more or less described by the 24-hourly wave of radiation. Details will be discussed in a separate paper.

Another conclusion is that an exhaustive analysis of heat diffusion in natural soil cannot be based solely on a depth-time frame of temperature observations, especially when one wants to understand the complexities of heat transfer during individual days, which is imperative in view of present-day detailed and accurate observational data, such as the Seabrook data. Supplementary observations, for example, the direct measurement of the heat flux B in a complete depth-time frame, are a necessity.

Instruments which give directly the soil-heat flux are available. We can mention the flat-plate type heat-flux meters which have been developed independently in various countries. One type is the Gier and Dunkle instrument [POPPENDIECK and VEHRENCAMP, 1952]. Similar instruments have been described and used by ALBRECHT [1935]. A shortcoming of this instrument type is the interference of the plate with the soil-water movements which may lead to extreme dryness of the soil overlying the plate, and subsequent disturbances in the field of soil-heat parameters. It might appear more promising to measure the heat conductivity rather than the heat flux; for example, with the Albrecht-type instrument employed by DE VRIES [1952], BRACHT [1949], MORSE [1952], and ALBRECHT [1935]. Even more desirable would be the direct measurement of the soil-heat capacity in situ, either by means of independent determinations of λ and κ or of λ and the product of λC; in the latter case, by employment of the temperature response at the surface of a known conductor rod buried in the ground and heated at a given rate. Excessive heating must of course be avoided.

Provided a sufficiently dense depth-time array of observation points is available, one can utilize the experimentally established relationships between the heat parameters and the soil-moisture content to derive the total mass of water contained in the unit volume and in vertical columns. Ramdas [MONIN, 1947] has used a similar method to determine the soil moisture. Further progress in these instrumental problems is desirable [GEIGER, 1950]. Information on time-depth dependencies of soil-heat parameters more detailed than now available would further the advancement of a theoretical microclimatology. In the previous attempts of the author to approach this problem [LETTAU, 1951; 1952] only the classical model of thermal diffusion in the soil could be considered mainly because of the lack of detailed information.

As a more concrete recommendation it is hoped that future abuse of the classical model of heat diffusion be avoided, especially the delusion of speaking of two "thermal diffusivities" of natural soil as derived from the phase shift and the amplitude decrement of soil-temperature oscillations.

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FREE-SURFACE INSTABILITY OF LIQUIDS IN STEEP CHANNELS

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Abstract--This paper reports observations and test results from experimental research concerned with the flow conditions under which the free surface of liquids in steep channels becomes unstable. The test results are presented through a graphical relation of a Reynolds number, a Froude number, and the inclination of the channel bottom to the horizontal.

Introduction--This investigation was a study of flow conditions at which instability of the free surface of liquid in a steep channel is initiated and the character of the flow downstream from the initial instability. In particular, the study was concerned with instabilities as they would develop in a two-dimensional flow over a smooth, fixed boundary, when the entering flow is steady. Those which may develop as a result of side effects were not a part of this study. However, such side effects did act as limits to the extent of this study.

Initial instability of the free surface was observed to develop either as well-defined waves or as what have been termed "bursts," giving the appearance of streamers. Although both occurrences were periodic and resulted in wave action downstream, the free-surface conditions were otherwise quite different in character.

Particular aspects of free-surface instability have received some attention from other investigators. There are a number of published papers that have been devoted to criteria for the existence of roll waves and a number that have explained the initiation of air entrainment on the basis of the turbulent boundary layer. In the latter group, that of HALBRONN [1952] is particularly noteworthy. However, there was evidence of a need for an orderly experimental study of the general character of initial instability and the resulting flow. It was the purpose of the study reported herein to fulfill this need, at least in part. Although boundary layer development is presumed to have been the cause of initial instability in all instances of this investigation, no attempt was made to determine the process of development.

Equipment--This research was conducted at the Hydraulic Laboratory, Cornell University, Ithaca, New York, where water is supplied to the Laboratory from a lake by means of a large-diameter pipe. From this source, the water was eventually passed through a two-inch diameter, flexible, rubber hose into the reservoir of a tilting, glass-walled flume. The test section of the flume is of steel framing, steel bottom base, and glass sidewalls. The inside width is 18 inches and the length 12 ft. The channel bottom was brought to as nearly a plane surface as practicable by installing a false, metallic bottom, which was considered to have a smooth surface. The flume is so constructed that it may easily be tilted to the desired inclination to the horizontal. The reservoir of the flume is equipped with a steel grid and wire mesh above its inlet to reduce kinetic energy of the entering stream. Flow from this reservoir into the flume is passed over a curved bottom surface.

Discharge was determined downstream from the flume by weighing the water collected in a container during a determined period of time. Stream depths were determined with a point gage. In view of the very small values of depth, the most satisfactory arrangement was a precision micrometer screw, used as a point gage.

Experimental procedure--The flume was tilted to arbitrary slopes, and, for each slope, the discharge was regulated so that instability of the free surface occurred at various predetermined locations along the channel. After each regulation of discharge, sufficient time was allowed to elapse in order that the inflow to the channel might be as free of externally induced disturbances as practicable. Instability of the free surface was detected by placing a light at the upstream end of the flume, and viewing the free surface from a position near the downstream end of the flume. From the reflection of light by the free surface, the location of initial instability could be seen. The depth of flow was measured normal to the channel bottom at a location immediately upstream from the disturbance of the initial instability. The discharge was determined in a manner previously mentioned. Temperature of the water was noted. Other data, not pertinent to this paper, were also recorded.

Test results and observations--Quantities important to this problem were related through dimensionless parameters that were considered to be appropriate. This relation may be expressed as the function

$$\phi\ (UD/\nu,\ U^2/gD,\ \theta) = 0$$

where D is measured depth of flow, U is discharge divided by the product of depth and width of flow, ν is kinematic viscosity, g is acceleration due to gravity, and θ is the angle of inclination of the channel bottom to the horizontal. The relation between the three dimensionless parameters above, as evidenced by the experimental data, is shown in Figure 1. The data from which the graph was prepared have been previously reported in a doctoral thesis by BALIGH [1953].

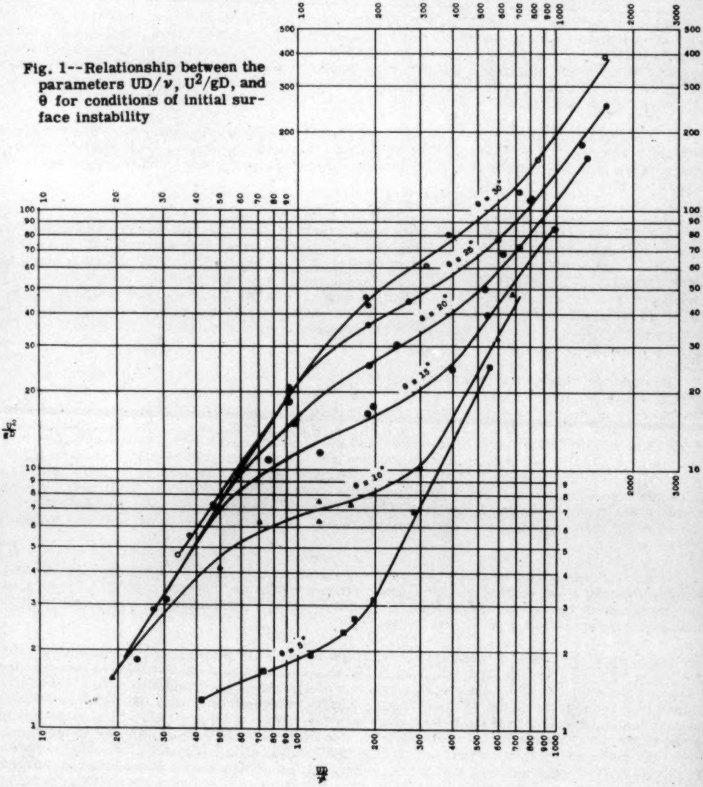

Fig. 1--Relationship between the parameters UD/ν, U^2/gD, and θ for conditions of initial surface instability

The parameter UD/ν is a Reynolds number, which is a rough index as to whether the flow is laminar or turbulent. An examination of the data represented in Figure 1 indicated that, for the lower values of this parameter, the flow was evidently laminar, and, for the higher values, evidently turbulent. The parameter $U^2/(gD)$ is a Froude number in a form that the authors believe to be convenient. If this form is corrected for slope and an assumed velocity variation in a direction normal to the channel bottom, it may be used as an index to identify the flow with respect to critical flow. An examination of the data represented in Figure 1 indicated that the mean velocity of flow in all cases was supercritical.

The curves of Figure 1 appear to approach a common, limiting curve at the lower values of UD/ν and $U^2/(gD)$. Under these conditions, the initial instability appeared as a smooth rise and rolling up of the free surface. Downstream, the water was clear in appearance, the free surface might be described as "oily" in appearance, and the flow was characterized by waves. Both wave height and wave length increased in the downstream direction, although this effect was not nearly as evident for the lower values of θ as for the higher values.

Considering the other extremity of the curves at the greater values of UD/ν and $U^2/(gD)$, the initial instability appeared as what have been described as "bursts." These "bursts" were periodic in nature, and spread as they progressed downstream. Downstream from the initial instability, the water was not clear in appearance, the free surface was broken and rough, and there was a basic wave action in the flow.

The observations of flow conditions downstream from the initial instability were limited by the equipment to relatively short lengths of channel. Consequently, no commentary is justified as to the ultimate flow conditions that may develop in a channel of considerable length. Further, limitations of equipment mean limitations in ranges of values for the measured physical quantities. Hence, Figure 1 shows only a part of the picture. It is the authors' belief that Figure 1 reveals relations of considerable interest, and that there is justification for further investigation directed at enlarging the picture.

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ON FACTORS GOVERNING SUBSURFACE STORM FLOW IN VOLCANIC ASH SOILS, NEW ZEALAND

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Abstract--The possible occurrence of subsurface storm flow in volcanic-ash soils was investigated by means of small lysimeters with and without window openings to measure lateral flow. The information obtained from the lysimeters led to a further investigation of apparently aberrant results by a number of experimental methods largely devised under field conditions. The results obtained from these experiments show that (1) a resistance to wetting exhibited by the surface soil at a low moisture content, (2) a low permeability of the B horizon compared with that of the A horizon, apparently related to an initial anisotropy in the ash beds, and (3) the transition from a fine to a coarse-textured layer cause a lateral flow through the surface soil on sloping ground to take place during rain storms. The magnitude of this flow largely depends on the intensity of a rain storm.

Introduction--Extensive beds of Taupo rhyolitic ash lie at the surface in the central part of the North Island of New Zealand. This volcanic ash is still in a relatively unweathered state and soil formed from it generally occurs as a sandy silt with many embedded pumice lumps, generally varying in size from that of a pea to that of a fist.

Fertility on slopes in this area generally increases from the top to the bottom as described elsewhere [VAN'T WOUDT, 1952]. Such a fertility gradient was presumed to arise from the effect of surface and subsurface storm flow. This paper is concerned with the latter flow only.

Many names have been assigned to this flow, but in this paper the nomenclature of HURSH [1936] has been followed. Hursh defined subsurface storm flow as that portion of the storm which filters into the surface soil but moves away through the upper horizons at a rate much in excess of normal ground-water seepage.

The subject was investigated on a slope of 56 ft in length and with an overall slope of 32° in "virgin" country under shrub, 15 mi east of Lake Taupo.

The slope is situated on the flank of an old river course, and thus extends evenly for a long distance which allowed the replication of experiments under practically identical conditions. The outline of the slope and the soil profile developed is shown in Figure 1. The soil development on the slope is typical for the area. It is seen that the A horizon increases in thickness from the top to the bottom; a B horizon is absent or poorly developed on the upper half, but it is better developed on the lower half and extends to 36 inches in depth at the foot of the slope. A few feet away from the slope on the flat, the total thickness of the soil (that is, a layer distinct by the coloration by organic matter and horizon development in this case) is only six inches. The permanent water table, according to borings made in the vicinity of the experimental area, is about 300 ft below the surface. Some figures on the mechanical composition of the soil are shown in Table 1.

The period of field work in this remote and isolated country was limited to one summer period, so that attention was focussed on the establishment of principles underlying any subsurface storm flow rather than on the determination of the magnitude of such a flow on a particular slope.

Experimental approach and results--As an initial approach, small lysimeters were installed at various levels along two trenches 38 ft apart and running from the top to the bottom of the slope. The lysimeters consisted of cylinders of galvanized iron with a diameter of five inches and mostly 12 inches long. In a number of cylinders a slit or window 2 3/4 inches wide was cut which extended from the bottom to just below the top. The lysimeters were tapped into the soil 15 inches away from the trenches, taking care that those with a window kept the same diameter. A collecting container was fitted around the base via a tunnel in the side wall of the trench. The windows, where present, were directed either up or down slope. Soil in the lysimeters was thus in undisturbed contact with the soil outside through the window. In this way they were presumed to trap lateral flow coming from higher ground, or to allow water filtering into the soil in the lysimeters to escape

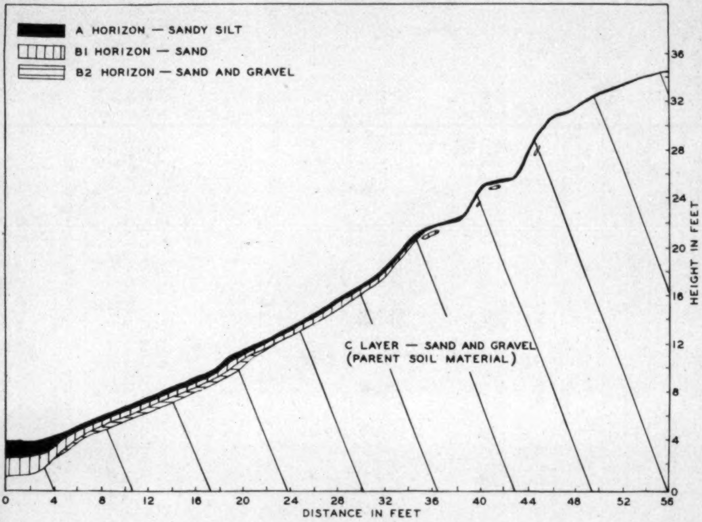
A HORIZON — SANDY SILT
B1 HORIZON — SAND
B2 HORIZON — SAND AND GRAVEL
C LAYER — SAND AND GRAVEL
(PARENT SOIL MATERIAL)
HEIGHT IN FEET
0
4
8
12
16
20
24
28
32
36
DISTANCE IN FEET
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56

Fig. 1--Soil profile of experimental area

Table 1--Mechanical composition

Position on slope	Horizon	Retained by two-mm sieve Pct air-dry weight	Material passed through two-mm round-hole sieve Pct ignited weight			
			Coarse sand	Fine sand	Silt	Clay
Top of slope	A	14.2	38.5	28.6	10.1	4.2
Upper slope	A	13.0	32.5	24.4	13.1	5.2
	C	16.7	60.6	23.8	9.1	0.7
Mid-slope	A	14.8	32.9	20.1	16.1	5.5
	B	18.6	38.7	33.3	7.1	2.4
Lower slope	A	10.1	24.6	23.1	17.1	7.3
	B	12.1	33.0	36.8	7.2	2.2
Foot of slope	A	55.1	34.1	15.4	14.1	4.0
	B	10.1	43.1	35.8	5.9	2.1
	C	12.7	71.5	21.9	2.1	1.1

Note: The ash deposit at the foot of the slope differs in geological origin from that on the slope.

laterally. The percolates were collected as much as possible after each rainstorm during the summer of 1950-51. The set-up of the lysimeters on the slope is shown in Figure 2 and the results are given in Table 2.

It is seen that there are some relatively small discrepancies between the individual yields and the size of the rain storms, which seem mainly related to the intensity of, and interval between, preceding storms; they will not be considered further in view of the purpose of this paper.

Table 2--Yield from lysimeters

Position on slope	Window	Soil depth in.		Date installed	Oct.	November 1950							Dec.	January 1951			Feb.		Total
					30	1	2	7	10	12	20	22	17	3	25	27	8	10	
					Preceding rain in inches														
		a	b		0.2	0.63	0.97	1.97	0.64	1.05	0.74	0.65	1.38	5.13	3.64	0.64	0.48	1.50	19.62
				1950	inch	inch	inch	inch	inch	inch	inch	inch	inch	inch	inch	inch	inch	inch	
Upper																			
L^{c}	no window	11	11	Oct. 29	0	0	0.48	0	0.03	0.02	0	0.23	0	0.89	0.57	0.13	0	0.13	2.48
R^{c}	no window	10	10	Nov. 10	...	...	...	...	...	0	0	0.01	0	0.87	1.07	0	0	0.09	2.04
L	window down	8	8	Oct. 29	0	0	0	0	0	0	0	0	0	0	0	0	0	0.38	0.38
R	window down	9	9	Nov. 10	...	...	...	...	...	0	0	0	0	0	0	0	0	0	0
Mid																			
L	no window	11	11	Oct. 29	0.03	0.09	0.55	0	0.09	0.02	0	0.36	0	1.24	1.32	0.31	0	0.72	4.73
R	no window	11	11	Nov. 10	...	...	...	...	...	0	0	0	0.08	0	0.45	0.10	0	1.09	1.72
L	window up	10	10	Oct. 29	0.09	0.20	4.92	0.18	0.48	3.12	0.65	0.79	1.29	8.35	6.02	0.06^{d}	0^{d}	0.97^{d}	27.12
R	window up	6	6	Nov. 10	...	...	...	...	...	0	0	0	2.53	6.58	4.61	0.40^{d}	0.04^{d}	2.58	16.74
L	window down	10	10	Oct. 29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R	window down	9	7	Nov. 10	...	...	...	...	...	0	0	0	0	0	0	0	0	0.37	0.37
Lower																			
L	no window	11	11	Nov. 6	...	...	...	0	0	0.39	0.34	0.48	0	2.29	2.01	0.42	0	1.67	7.60
R	no window	11	11	Feb. 3^{e}	...	...	...	...	...	...	...	...	...	...	...	...	0	1.73	1.73
L	window up	10	8	Nov. 6	...	...	...	0	0	0	0	0	0	6.62	1.99	0	0	1.48	10.09
R	window up	8	8	Feb. 3^{e}	...	...	...	...	...	...	...	...	...	...	...	...	0	1.45	1.45
Foot																			
L	no window	20	20	Oct. 31	...	0.21	0.77	0.02	0.02	0.19	0.03	0.10	0.20	3.72	1.56	0.42	0	1.63	8.97
R	no window	11	11	Oct. 30	...	0	1.12	0	0	0.33	0.36	0.63	0.14	3.77	1.22	0.47	0	1.52	9.56
L	window up	15	13	Oct. 31	...	0	0.32	0	0	0	0.01	0.01	0.17	2.31	3.98	0.02	0.02	1.60	8.44
R	window up	10	8	Oct. 30	...	0	0.64	0.57	0.01	0	0.03	0.06	0.98	5.86	3.57	0.10	0.12	6.57	18.51
R	window down	11	8	Oct. 30	...	0	0.53	0	0	0	0	0	0	1.72	0.47	0	0	0.99	3.71

a and b: Depth of soil in lysimeter, respectively before and after removal of part of the B horizon.

[c] L and R for lysimeters along left-hand and right-hand trench respectively.

[d] Collecting container leaking.

[e] 1951.

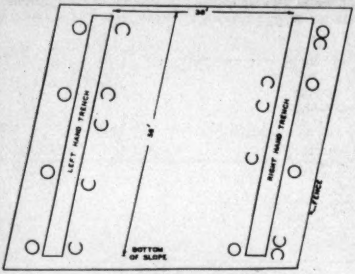

Fig. 2--Arrangement of lysimeters on experimental area

The results indicate that on the upper half of the slope (collected at mid-slope) a substantial lateral flow had taken place, which was caused by a resistance to wetting exhibited by the soil at a low moisture content, as will be discussed on the following pages.

On the lower half and at the foot of the slope, little or no lateral flow could be demonstrated; in fact, the yields from the lysimeters with a window directed up-slope sometimes were initially lower than those from the lysimeters without window. This was investigated by a number of methods which are discussed below.

Resistance to wetting--At an early stage it had been noted that dried-out top soil in this particular area was difficult to re-wet and caused surface storm flow to take place during rainstorms. A certain thickness of the very top layer always became wetted during the storm, and water flowing over the surface for some distance disappeared on reaching small hollows.

The surface soil on the upper half of the experimental area generally dried out within a day after a rainstorm and in that state was difficult to re-wet. On the lower half of the slope most soil of the A and B horizons similarly exhibited a resistance to wetting, but under field conditions during the five months of observation the soil in this position rarely dried out to such an extent for resistance to wetting to become a factor of significance.

The barrier to infiltration, which resistance to wetting creates, was first examined in infiltration experiments using cores of undisturbed soil in a field laboratory. The soil could be made to wet by leaving water in contact with the soil during a time varying from a few minutes to several days. Impact by rain drops accelerated the wetting. Penetration to lower depth in the cores took place along roots and through channels. Similarly under field conditions it could be observed that, even where the top few inches had remained partly or almost wholly dry, the readily wettable subsoil (the C horizon) had generally become wetted in pockets and strands and heavy rain caused the subsoil to become wetted to a considerable depth, leaving unwetted pockets in the top soil.

The significance of resistance to wetting in causing subsurface storm flow was further investigated under laboratory conditions, first using models of dune sand. Dune sand was collected from Paekakariki on the west coast of the North Island. This sand similarly showed a resistance to wetting when air dry.

Air-dry sand, with a moisture content of three per cent by weight, was modelled in trays, measuring 12 × 15 inches and having an upright rim of two inches, into micro-relief with slopes up to eight inches long and heights up to six inches above the lowest level. Water was evenly applied to the models by overhead spraying by an ordinary insecticide pump and inside a glasshouse to avoid wind effects. An example of a "wetting profile," produced by about half an inch of rain applied over an hour, is shown in Figure 3. No runoff over the surface had taken place.

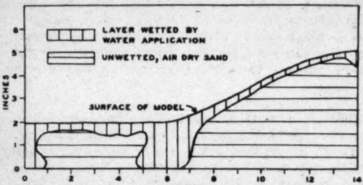

Fig. 3--Moisture distribution in model of air-dry dune sand after application of about half an inch of rain

It is seen that on the slope only a thin layer had become wetted, but that at its foot the thickness was considerable. Much of the water applied to the slope had moved through the wetted layer and on top of the still unwetted soil lower down, and on reaching the foot of the slope had given rise to the wet pocket as was proved by the following experiment.

Figure 4 shows a rounded sand model. Strips of blotting paper soaked in a starch solution were placed underneath the sand on the floor of the tray with part of the paper protruding. The sand was first wetted by spraying which produced the wetting profile shown in Figure 4, and instead of water a few milliliters of potassium iodide solution were then applied by a pipette to the highest point, taking care that no fluid flowed over the surface. Within two minutes the paper at the bottom turned blue. Replications gave the same result.

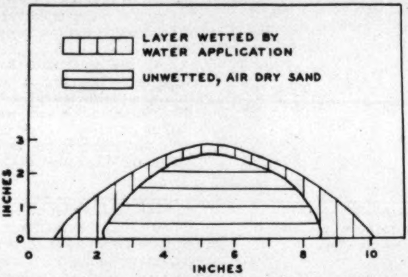

Fig. 4--Cross section of sand model used for following path of KI_3

If models were used with a steeper slope than that shown in Figure 3, the rate of application had to be slower, as otherwise runoff tended to take place over the surface. In general, the rate had to be such that the wet layer on the slope was thick enough to be able to conduct further applied water through it. This is related to the fact that a prolonged application of water gradually increased the thickness of the wet top layer on the slope.

A great number of experiments was carried out to determine at what moisture content the effect of a resistance to wetting persists; in all of them the results showed that this effect ceases at a moisture content two or three per cent above that of air dry.

Similar results were obtained with models of volcanic ash soil, passed through a two-mm round-hole sieve, but in a model of air-dry Tokomaru clay loam, a soil which is readily wettable in that state, no lateral drainage could be demonstrated.

Anisotropy--The amounts initially collected from the lysimeters seemed to indicate that little subsurface storm flow occurred on the lower half of the slope. Meanwhile, surface storm flow was measured by small runoff traps placed at four levels on the slope in triplicate. It was found that this flow was of almost negligible significance in the area. Subsurface storm flow thus seemed to be the only factor which could explain the observations made on the fertility gradient on this slope, as determined by chemical analysis [VAN'T WOUDT, 1952], and the general soil development on the area. It was thus presumed that lateral flow had not been trapped on the lower half of the slope. This was investigated by a number of experimental methods which revealed that two more factors governed subsurface storm flow, as described under this and the following heading.

First of all, infiltration experiments were carried out in a field laboratory, using cores of undisturbed soil collected from various levels along the lower slope. For this purpose, square containers were used which measured three by three inches and varied in length from nine to 14 inches. They were open at the top and bottom and were provided on one side with a window (simply openings in the container) 2 1/4 inches wide, which extended from the top to the bottom except for a narrow bridge on each side to keep the container in shape and to provide a cutting edge at the base. Rain was simulated by applying water from a burette provided with rubber tubing near the outlet, which allowed an even spreading of applied drops over the surface by moving the outlet by hand.

Water was initially applied as rapidly as it could be taken up by the surface soil (the A horizon). Although soil just taken from the field was used, probably not far below "field capacity," the advance of a "wet front" could be followed through the window by the more moist appearance in this particular soil. It could thus be seen when the wet front reached the top of the B horizon. At that time the rate of application had to be slowed down considerably as otherwise water "bulged" out of the soil just above the B horizon, and tended to flow along the side wall, as seen through the window. Replications with soil from various positions on the slope yielded the same result; the B horizon appeared to be a barrier to rapid infiltration.

This was further checked in the field, measuring the maximum rate at which water could be taken up by the top soil (A horizon) and the underlying top of the B horizon, after the overlying soil had been removed. In five replications it was found that the infiltration rate of the A horizon was about twice that into the B horizon. Having gained this information, it was visualized that the low yield from the lysimeters provided with a window on the lower part of the slope could be due to the blocking effect of the B horizon. Thus infiltrating water on reaching the B horizon in the lysimeters could not, with high application rates, pass through rapidly enough. It escaped laterally through the window.

Part of the B horizon was then removed from the bottom end of the lysimeters on December 18, 1950, and higher yields were obtained after that date as shown in Table 2, summarized in Table 3.

Table 3--Lysimeter yield as a percentage of rainfall before and after removal of part of the B horizon

Location	Window facing	Percentage of rain recovered	
		before	after
Left hand trench			
Lower slope	Upslope	0	88.6
Foot of slope	Upslope	6.2	69.6
Right hand trench			
Foot of slope	Upslope	27.7	142.4
Foot of slope	Downslope	6.4	27.9

Table 4--Pore space as a percentage of the total volume occupied by the soil

Position on slope	A horizon		B horizon		C horizon	
	Depth from surface	Pore space	Depth from surface	Pore space	Depth from surface	Pore space
	inch		inch		inch	
Top	0 - 3 1/2	71.3	.....	...	5 - 7	70.8
Top	0 - 3 1/2	68.6	.....	...	7 - 9	77.2
					8 - 10	69.5
					8 - 10	70.8
Upper	0 - 3 1/2	74.7	.....	...	18 - 20	65.5
Upper	0 - 3 1/2	73.5	.....	...	18 - 20	64.7
Mid	0 - 3 1/2	72.9	6 - 8	72.8	16 - 18	74.5
Mid	0 - 3 1/2	75.3	5 - 7	68.3	16 - 18	71.5
Lower	0 - 3 1/2	73.5	5 - 7	67.1	13 - 15	68.4
Lower	0 - 3 1/2	76.7	5 - 7	67.6	13 - 15	68.3
Foot	0 - 3 1/2	79.1	12 - 15	71.0	38 - 40	66.0
Foot	0 - 3 1/2	83.0	12 - 15	73.0	38 - 40	67.2
Foot	4 - 6 1/2	70.5	15 - 18	73.6	.....	...
Foot	4 - 6 1/2	68.3	15 - 18	72.5	.....	...
Foot	......	...	22 - 24	69.4	.....	...
Foot	......	...	22 - 24	70.9	.....	...
Average		74.0		70.6		69.5

From about 20 determinations of the moisture content at the wet front in this soil, it was found that at this level generally 50 pct of the soil volume in situ is occupied by water, leaving 20 to 30 pct or more occupied by air (Table 4). The remaining 20 or 30 pct consists of air trapped in the inside of pumice particles (which causes particles to float on water) and by air in large pores. Infiltration experiments in the field and in the laboratory showed that on using coarse particles (diameter between one mm and one cm) water moves as a film around the larger particles and does not fill the large pores between them. Thus water filtering rapidly into the A horizon, on reaching the B horizon, builds up in the A horizon by the further replacement of air so that on sloping ground a rainstorm of a certain intensity causes a lateral flow to take place through large pores in the top layer to the foot of the slope.

The total pore space as a percentage of the volume occupied by the soil in situ in various positions on the slope is shown in Table 4. It is seen that the B horizon has only little less pore space than the A horizon; the subsoil (C horizon) shows the lowest volume of pores. Yet the A and the C horizons show about the same infiltration rate, and the pore volume of the B horizon would certainly not suggest a much reduced capacity.

An explanation may be found in the configuration of the pore space rather than in the total pore volume present. The ash deposits are sedimentary ones, and the general observation for sedimentary deposits would imply that they are more permeable in a horizontal than in a vertical direction. An initial substantial difference in permeability in these porous beds because of anisotropy could not be expected, but anisotropy could explain a reduced infiltration rate at lower depth in the soil profile because pore space would tend to become blocked more in a horizontal than in a vertical plane by material brought down by percolating water.

A fine-textured layer overlying a coarse-textured one--A low infiltration rate of the B horizon was not taken to constitute a complete and satisfactory answer for the low yields obtained on the lower part of the slope. The escape of infiltrating water through the window was further studied by experiments with a new lysimeter installed at the very foot of the slope; this contained only six inches of soil of the A horizon and over that distance was continuous with the surrounding soil.

A great number of infiltration experiments was carried out, applying water at first from a measuring cylinder and later from a burette which was placed over the lysimeter, simulating rain as described before. When water was applied as rapidly as it could be taken up by the soil, which for one inch of rain only took a few minutes in this case, most of the applied water was recovered in the empty collecting container placed underneath. On reducing the rate, less and less water was recovered, and when half an inch of rain was slowly applied over several hours not a drop was recovered. In that case all the applied water had moved away laterally through the window.

The collecting container was then filled with sandy silt from the A horizon and an attempt was made to establish a good contact between the soil in the lysimeter and that in the collecting container. The amounts recovered were found by weighing the container before and some time after the application of water. The results showed again that the amount of water recovered decreased as the rate of application was reduced. Incomplete recovery, where this occurred during rapid application, was largely ascribed to the lack of good contact between the soil in the lysimeter and that in the collecting container.

The interest, however, circles around the use of coarser material from the subsoil (mean diameter about one mm) in the collecting container. On applying water as rapidly as possible, most of it was recovered in the subsoil material as was the case with the empty collecting container. On reducing the rate of application much less water was collected than where top soil had been placed in the container, but more than where the container had been empty. As an example, from 0.75 inch of rain applied over 2 1/2 hours, 0.36 inch was recovered using top soil, 0.17 inch using subsoil, and none where the collecting container had been empty.

Thus, where the top soil was underlain by coarser material there was more lateral flow than where the soil had been more or less homogeneous throughout. This is further illustrated by experiments carried out at a later date with soil of the same type collected from a more accessible area.

Sheets of celluloid of appropriate size were graduated in inches with India ink and rolled into cylinders four inches in diameter and 24 inches long, fastening the two ends together by cellotape. The cylinders were then slightly greased on the inside and placed vertically on a large Petri dish. They were then evenly packed with air-dry soil in three different ways, as follows: Cylinder 1--18 inches soil from A horizon, passed through one-mm-round-hole sieve; Cylinder 2--six inches of the soil of Cylinder 1, underlain by 12 inches of gritty subsoil material passed through a two-mm but retained by a one-mm-round-hole sieve; and Cylinder 3--six inches of the soil of Cylinder 1, underlain by a mixture of the above soil and the subsoil of Cylinder 2 with the proportion of coarse soil gradually increasing with increase in depth.

An inch-thick layer of gravel (which was removed before analysis) was placed on top and water was simultaneously applied to the upper surface of the soil in all cylinders till the wet front had penetrated to six inches depth. The moisture level of the wet front was determined immediately after the water application in a separate experiment and was found to lie at about 75 pct by weight.

The cylinders were left to drain for four days. Evaporation was largely prevented by placing an inverted Petri dish over the top. The cylinders were cut up into inch slices by burning the celluloid by applying a current to Nichrome wire wound around the cylinders at the inch marks. The soil was removed by sliding a thin metal sheet into the gap thus formed. The moisture content in the top six inches, gravimetrically determined, was found to be as shown in Table 5.

Table 5--Moisture in the top six inches of test cylinders

Location	Cylinder 1	Cylinder 2	Cylinder 3
	pct	pct	pct
Top inch	53.2	65.6	57.9
Second inch	53.9	66.6	58.6
Third inch	52.9	66.6	58.1
Fourth inch	52.9	66.6	59.8
Fifth inch	53.9	67.9	60.3
Sixth inch	51.3	68.7	59.2
Average	53.0	67.0	59.0

These observations may be viewed in the light of the "out-flow" law, formulated by RICHARDS [1950], and the work done by MOORE [1939] on Yolo clay and Oakley sand. In the Yolo clay the pressure potential at the wet front was found to be -140 gm cm/gm, which corresponded to a moisture content of 26 pct on an oven-dry basis. In the Oakley sand the pressure potential below which "capillary permeability" was zero was found to be -80 gm cm/gm. Thus, as Moore remarked, for water to move from the Yolo clay into underlying Oakley sand, the pressure potential in the clay had to increase from -140 gm cm/gm to more than -80 gm cm/gm. A pressure potential of -80 gm cm/gm in the clay corresponded to a moisture content of 30 pct, being thus four per cent higher than that at the wet front in uniform clay.

Thus for water to move from a fine top soil into a coarser underlying layer the moisture content in the top soil has to build up to a level above that of the wet front in homogeneous material until a pressure is reached at which water can move into the coarse layer. The transition need not be a sharp one; gradually increasing textural coarseness with increase in depth below the surface has the same effect.

The moisture in excess of that necessary to bring the soil to the moisture level of the wet front, but below that necessary to produce outflow (either into open space as in the lysimeters or into an underlying coarser soil) causes a build-up in the surface soil and a lateral flow to take place through large pores to the foot of the slope similar to the case discussed under the preceding heading.

The conclusion has thus been reached that because of this factor subsurface storm flow will take place during rainstorms of certain low intensities and infiltration into underlying coarse soil will then take place only when the rate of application exceeds the rate at which water can move away laterally through a finer overlying top soil.

Conclusions--Subsurface storm flow in volcanic ash soils takes place as a result of the effect of three factors, each of which obstructs a rapid vertical infiltration at some depth in the soil profile during rainstorms.

Firstly, it takes place through a relatively thin layer at the surface, which has become wetted in the course of a rainstorm and on top of still unwetted soil.

Secondly, during rain of a certain relatively high intensity, a low infiltration capacity of the B horizon compared with that of the A horizon causes a build-up of moisture in the latter layer which results in a lateral flow through that layer to the foot of the slope.

Thirdly, a similar build-up and lateral flow takes place where application of water to the surface is not rapid enough to increase the pressure potential sufficiently for water to move from a fine top soil into underlying coarser soil.

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DAYTIME PARTITION OF IRRADIATION AND THE EVAPORATION CHILLING OF THE GROUND

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Abstract--The present study concerns daytime conduction and convection at the ground; how added soil moisture magnifies the heat-flow cycle; and how latent heat of vaporization offsets the diurnal temperature cycles. Measured diurnal cycles of net radiation, conduction, and convection for dry ground are formalized to show how the amplitudes and phase lag of half-cycle temperature and conduction waves indicate the partition of energy at the ground surface. A series of four test plots of five acres each was studied during the spring frosts in a pear orchard near Lakeport. Two plots were disk-cultivated, and one of these was immediately flood-irrigated lightly. The observed diurnal magnitudes of heat flow were more than twice as great in the watered plot as in the unirrigated. The striking results are not the effect of disk cultivation but rather that of the chilling caused by application of water. The watered plot took more than ten days (in April) to recover from the evaporation chill (but then warmed up more than the other three plots and two weeks after flooding was definitely less liable to frost than the unwatered plots). These investigations have the considerable advantage of direct measurement of heat-conduction rates into and out of the ground. Much remains to be done, however, to establish empirical coefficients to be used with simplified formulas. The measurement of evaporation is an important future objective, but knowledge of total daily water loss from the soil can be used in the formulas to get a fair understanding of the diurnal thermal system.

Daytime heat balance at dry ground surface--It is usual to ignore evaporative cooling when treating the diurnal temperature cycle in soils, but this omission may lead to erroneous conclusions. The role of moisture exchange cannot be understood, however, without a working knowledge of the heat-transfer rates of radiation, conduction, and convection. The entire heat-balance system is restricted to these three modes only for bare, dry ground. Our best example of this simple case is given in Figure 1, which shows the results of careful continuous measurements of heat-flow rates and temperatures in a joint project under H. F. Poppendiek [VEHRENCAMP, 1951] when no soil moisture could be measured with excellent instruments used by S. J. Richards. Although the wind was not constant, the following features are of interest: (a) The actual whole-spectrum net radiation is only 2/3 the short-wave insolation; (b) the peak heat flow by conduction into the ground occurs 2 1/2 hours before peak net radiation; (c) the ground heat flow reverses at 15h 00m when the irradiation has fallen only to 1/2-peak value; (d) vertical convection of heat from the soil surface has its maximum one hour later than the net radiation; (e) at 17h 00m the air convection is still so strong it is carrying away all the impinging net radiation and also an equal rate of soil heat conducted upward to the surface; (f) in the first part of the night, reversed air convection supplies about 20 pct of the net outgoing radiation; but (g) before sunrise the soil heat flow matches the nocturnal radiation loss when the temperature difference between the soil surface and air at 02h 00m is practically zero.

Items (d) and (g) were magnified by the inflow of an air mass unseasonably cold relative to the deep-ground temperature, but the main relationships of the three heat flows are nearly typical for clear windy-day heat balance without moisture transformation. (Under ordinary moist ground conditions with the air at 05h 00m having a dewpoint well below the surface temperature of 40°F, evaporation would have occurred; and the heat flow from the ground would necessarily have exceeded the net radiation demand [CHIN, 1951].) Because of increasing wind the peak temperature of 128°F in ground surface occurred early at 12h 00m PST closely following the net radiation peak, but the 81°F peak in air temperature at 15 m is at about 14h 00m, an hour later than the peak in convection. The delay in the convection peak can be ascribed to eddy diffusivity still increasing with wind velocity.

Daytime irradiation partition into conduction and convection--For a substantial understanding of the influences on surface temperature of changes in thermal conductivity and capacity of the soil and of the eddy-diffusivity in the air, it is necessary to establish appropriate heat-flow formulas with these factors as variables. The main connection between the daytime and nighttime heat flows is, of course, the heat storage in the soil. Considering the daytime heat cycles separately from the

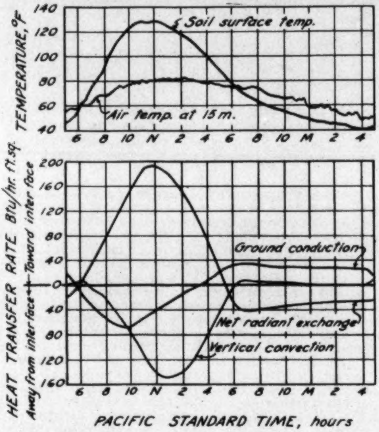
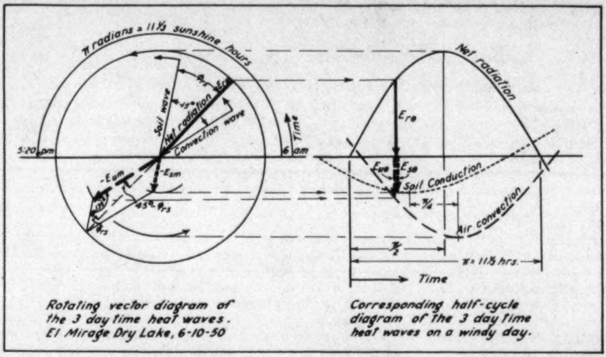


Fig. 1--Whole-spectrum net radiation exchange, ground heat conduction, and vertical convective heat-transfer rates, at a dry and very smooth, hard ground surface, El Mirage Dry Lake, Calif., June 10-11, 1950, from Vehrencamp [1951] and corresponding surface and 48-ft air temperature; the heat rates show that for this case having no evaporation 27 pct of the daytime net radiation entered the ground and 73 pct went into the air by convection, and that before sunrise the outward soil heat conduction completely supplied the nocturnal radiation demand

usually steady-cooling system at night, the systematic increase and decrease of temperatures and heat-flow rates from sunrise to sunset can be considered as sine-wave approximations which in fact might be expected from the hourly progression in the angle of incidence of sunshine. The relatively steady condition at night interrupts the concept of repetitive cycles but does not invalidate the use of half-cycle sinusoidal analysis for daytime conditions. By separation, therefore, the respective analyses for daytime and for nighttime heat transfers can each be relatively simple mathematically and can readily include the seasonal change in length of day. MERSMAN [1942] derived the basic relation between the partial cycles of applied heat and of resulting surface temperature. He showed that the time lag for the surface temperature behind heat flow in a single medium approaches 1/8 cycle only as the actual temperature distribution approaches that which would occur with repetitive full cycles. Thus the three-hour separation called for by LETTAU [1952] is not exact. More significant is the time lag between peak heat flow into the ground and noontime peak irradiation. In the real system shown in Figure 1 having both soil and air for heat transfer the irradiation is seen near noon to be more nearly in phase with surface temperature than with soil heat flow. This means that most of the net radiation must be going into convection.

A simple analytical treatment of the heat curves is suggested by the shape of the curves in Figure 1. The measured daytime net radiation is practically a perfect half sine wave, and the convective heat flow can be fairly well fitted with a sine curve of the same period (Fig. 1). The ground conduction curve has a shorter period, but even in this case if we can skip over the time from the beginning of soil-heat inflow at sunrise covering the steep rise till about 10h 00m PST, the rest of the conductive heat flow can be fairly matched by a sine curve having a half-cycle period of the same number of hours as that for the other two heat flows. This assumption of equal periods immediately makes possible simple analytical treatment for the daytime, because each heat wave can then be approximated by the projection of its peak maximum as a vector rotating counterclockwise, always keeping the three respective vectors in the same relative positions as pictured in Figure 2. As mentioned above, the time lag between soil-heat flow and air convection (nearly coincident with soil-surface temperature) is not necessarily 45°, but the vector diagram of three components can



Rotating vector diagram of the 3 day time heat waves. El Mirage Dry Lake, 6-10-50

Corresponding half-cycle diagram of the 3 day time heat waves on a windy day.

Fig. 2--Analytical diagram of daytime, half-cycle heat flows approximating Figure 1

always be solved as a parallelogram of three amplitudes. Furthermore, the relative positions of the three peak times indicate geometrically the relative magnitudes of the effective amplitudes.

Daytime partition of irradiation including evapotranspiration--When there is a moisture change of state involving considerable latent heat in the daytime cycle, the four modes of heat transfer can be treated as a three-component balance if the latent heat transformation can be assumed either in phase with convection or with net radiation. In general, transpiration is directly associated with sunshine, and hourly soil-moisture evaporation is directly associated with convection. Thus by correcting the measurement of net radiation by the estimation of hourly transpiration loss, and having direct measurement of conduction into the ground, we can still estimate the unmeasurable heat-flow rate by convection (including surface evaporation) from the amplitudes and also from time lags of the measured components. The immediate advantage in these procedures is that they reveal the relative importance of net-radiation rate, wind, soil conditions, and moisture in the daytime heat balance and how they influence surface temperature. This half-cycle method of approximation provides, therefore, a means of calculating daytime temperatures from about 10h 00m to sunset using empirical heat-transfer coefficients much the same as we have done for nocturnal orchard temperature [BROOKS and Others, 1952].

The formulas relating the part cycle of daytime soil conduction with surface temperature can be approximated by the full-cycle equation because usually the temperature profile in the soil by mid-morning is substantially what would have resulted from a full-cycle heat wave. Such cycles are commonly used to determine decrease of temperature amplitude with depth [GEIGER, 1950, p. 29]. The effect of changing the magnitudes of thermal characteristics of the soil can thus be judged by the formula for maximum surface temperature in degrees Fahrenheit, namely

$$t_{\max, z=0} = A_0 + E_{sm} / \sqrt{kc_\gamma \omega} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

In other words: For an applied sine wave of heat, the resulting maximum soil-surface temperature is specified by the daily mean soil temperature A_0 plus the amplitude of the peak heat-conduction rate E_{sm}, divided by the thermal admittance $\sqrt{kc_\gamma \omega}$. It is to be noted that for cyclic heat flow into a semi-infinite slab the thermal conductivity does not act alone, but with volumetric heat capacity and to the 1/2 power [JAKOB, 1949, p. 297]. And as mentioned above, any change in surface temperature affects the partition of energy between the soil and the air and consequently the heat conduction wave amplitude.

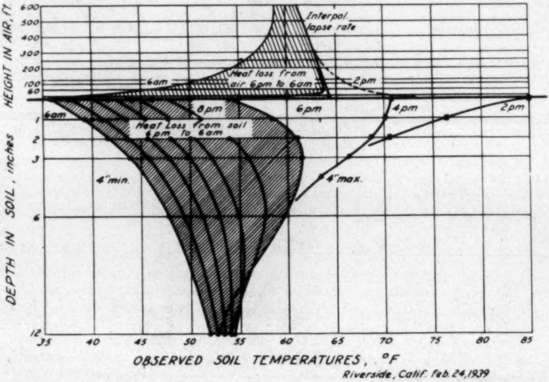
The formula for daytime heat flow from the surface to the air by convection is determined primarily by temperature gradient in the air and eddy diffusivity, [POPPENDIEK, 1952]. These factors vary strongly with height in spite of a reasonable constancy of vertical heat flow [GEIGER, 1950, p. 41]. We find it more convenient, therefore, to utilize the engineer's concept of surface-transfer coefficient based on air velocity and the difference between soil-surface temperature and the temperature of air at considerable height. The formula developed on this system by BROOKS [1951] for maximum convection rate in Btu/hr ft^2 is

$$E_{um} = m_t \, C'_{Hz} \, U_o \, E_{sm} / \sqrt{kc_\gamma \omega} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where m_t is a coefficient of thermal turbulence varying with buoyancy stability, and C'_{Hz} a combined heat-capacity and friction factor modified for difference in mean temperatures of air and soil, U_o is the wind velocity; and, as in (1), $E_{sm}/\sqrt{kc_\gamma \omega}$ is the daytime amplitude of the soil-surface temperature wave. These two equations and the vector method of determining heat balance, Figure 2, provide the desired insight as to how changes in thermal characteristics of the soil and in convection rates in air affect daytime soil-surface temperature. The actual degree of change can be predicted as soon as appropriate tables of adjustment coefficients have been established by experience.

Bearing in mind that the incoming net radiation must be balanced at all times by the sum of the convective, conductive, and latent heat flows, any change in the rate of one must be compensated by a change in rate of the others. It can be seen in Figure 1 by the areas under the curves that in this dry example about 27 pct of the daytime net radiation went into the ground and 73 pct into the air. This partition of energy rates is very different from that indicated by GEIGER [1950, Fig. 1], but it is as expected in this dry case because of the unusual conductances depending on wind and dry ground. For example: If there is no change in surface temperature or in wind velocity but the soil admittance ($\sqrt{kc_\gamma \omega}$) is doubled, the new partition of heat flow increases the ground conduction from 27 to 54 units while the air convection remains at 73 units. This would then dispose of 127 units instead of 100, so the temperature potential of the surface would correspondingly drop the maximum about 12°F from the original dry-ground example, and the new percentages would be 44 and 56 pct respectively for daytime heat flows into the ground and into the air. In the winter any such increase of heat flow into the ground brought about by increasing soil conductivity would raise the average temperature of the soil and might be thought to decrease frost hazard by the storage of more daytime solar energy. This has been found to be an excessive over-simplification when water is used to increase the conductivity of the soil.

Determination of soil conductivity and estimation of nocturnal eddy convection--Although the soil is never a homogeneous substance with uniform thermal characteristics throughout, the ground



Riverside, Calif. Feb. 24, 1939

Fig. 3--Rate of nocturnal heat loss from soil and air, as indicated by drop in temperature, at two-hour intervals; the depth in soil is plotted at a ratio of 1500 to 1 as compared to the height in air, so that the shaded areas indicate the same heat capacity per unit area; about four times as much heat is lost from the ground as from the air during typical radiation frost night, and most of the ground heat comes from the upper six inches, very little below 12 inches as a solid of considerable heat capacity reacts to a steady heat loss very much as would a semi-infinite slab. It is possible, therefore, to use a measurement of soil heat flow under steady nocturnal radiation conditions to determine soil conductivity in situ simply by also measuring the temperature gradient. The temperature profiles in Figure 3 near the surface show that the soil temperature gradient is practically constant on clear, calm nights in February from midnight to 06h 00m (this figure has the general shape called for by LETTAU [1951] except that the minimum surface temperature occurs at 06h 00m, while his 24-hour cycle treatment places the minimum 12 hours after the maximum). Furthermore, since the gradient is also nearly linear in the upper few inches, it can be evaluated by measuring soil temperatures at two depths, namely, near the surface and at a depth of two to four inches.

The nocturnal downward heat flow from overhead air by eddy convection follows much the same pattern as heat flow from the ground. But because we have no way of directly measuring convective heat flow we must approximate it by subtraction of measured soil heat flow from measured net radiation exchange. Unfortunately, this leaves undetermined the heat involved in the condensation and evaporation of moisture. Ordinarily with a wind, so much heat is available from such a huge depth of air that there is no frost hazard. Conversely, on very calm nights of excessive stability there is very little eddy convection, and a thin layer of air near the ground quickly drops in temperature because of the inherently small heat capacity of air. When latent heat is available from dew formation, it can logically be included in with convection at night, but in the opposite sense if it is for evaporation of soil moisture.

Combined soil and air heat-transfer relationships at bare-ground surface during nocturnal radiation cooling--Under the observed net radiation loss, which was practically constant, and considering heat from the soil and air as supplying the entire radiation demand at the surface, the diagram in Figure 3 shows the nocturnal sweep of soil temperatures according to measurements at Riverside in 1939 and the corresponding air-temperature profiles interpreted for bare ground from measurements from 20 to 60 ft above the surface and interpolated radiosonde data. The ordinate scales for air and soil are chosen 1500 to 1 to represent graphically the same heat capacity; thus the shaded areas represent the proportional heat sources for the total energy radiated to the sky during the night. A considerable part of the heat lost by the air is by short-distance, water-vapor radiation, which is part of the measured back radiation. The part of the air heat coming by eddy convection is therefore less than indicated by the shading. For the Riverside example the convective air heat amounts to about a fifth that given up by the soil since that is the difference needed to match net radiation. This bare-ground exchange is, of course, too simple for an orchard, but the pattern of Figure 3 can be expanded by considering the air interface as at slightly below tree-top level. The important unsolved problem is the effect of moisture.

Trial of soil moistening for frost protection near Clear Lake, California--To get some measurements of the thermal effects of irrigation, a series of test plots was studied for spring frosts in a pear orchard near Lakeport. These plots were adjacent, of five acres each, and with their long axes in the direction of pre-sunrise air drift. One check plot was left with cover-crop, which was very sparse and only about 12 inches tall, much bare ground being visible. Another plot was oil-sprayed to kill the cover-crop. On April 18 and 19, 1949, two plots were disk-cultivated, and one was immediately flood-irrigated lightly. Figure 4 shows the immediate, great differences in diurnal temperature and soil heat-flow in the two cultivated plots (one not irrigated), both having been substantially alike before the irrigation. Peak heat-inflow rate doubled in the irrigated plot, rising from 38 to 78 Btu/hr ft^2, while the 1/8-inch soil-temperature minimum fell from 130° to 93°F. But at the same time the mean temperature at four-inch depth in the irrigated plot dropped seven degrees Fahrenheit relative to the unwatered plot. Figure 5 shows that the watered plot took more than ten days to recover but then warmed up more than the other three plots and two weeks after flooding was definitely less liable to frost than the unwatered plots. The observed relative magnitudes of daytime heat intake that are two or more times greater in the watered plots could have been anticipated for the daytime from increased thermal conductivity, but the large heat flow at night in the orchard, though less than the open-sky net nocturnal radiation, needs further explanation. We believe this is found in nocturnal evaporation.

The nocturnal conduction rates shown in Figure 4 are not exactly comparable because the soil heat flow meters were buried under the edges of different trees and necessarily "saw" different fractions of the sky hemisphere. Previous data on the plot two days before irrigation show a soil-temperature difference of 18°F between the four-inch depth and the surface. This difference decreased to nine degrees Fahrenheit one day after irrigating, as was expected from heat-transfer studies described with Figure 1. In the same period the soil-heat flow increased from 10 to 12 Btu/hr ft^2 when a slight decrease was expected because there was a decrease in nocturnal loss rate in the control plot, and the surface temperature was two degrees Fahrenheit colder in the moist plot. The discrepancy seems to be about three Btu/hr ft^2.

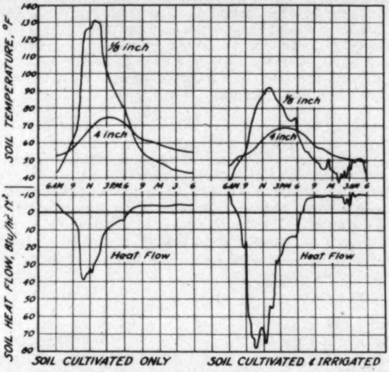


Fig. 4--Influence of irrigation on the heat conduction in the ground and on soil temperatures in a pear orchard near Lakeport, Calif., one week before a late spring frost; the heat-flow meters buried 1/8 inch between trees did not have identical sky exposure but show clearly a doubling of heat conduction in the watered plot

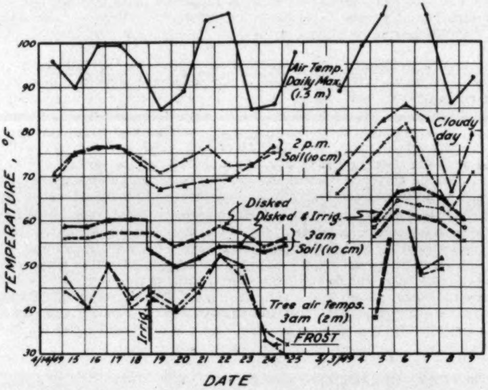


Fig. 5--Daily temperature sequences in irrigated and non-irrigated plots near Lakeport showing a seven-degree Fahrenheit evaporation chill April 19, 1949, and failure to recover before a late spring frost April 25, 1949, but subsequently a relatively warmer orchard temperature in the plot that had been irrigated

Rate of daily evaporation of soil moisture from a bare surface--The degree of evaporation chill naturally depends on how rapidly water is vaporized, which in turn depends on whether the soil surface is wet, whether the surface is down to field capacity, or whether partial surface drying has already occurred. Since observations of water-vapor gradient are lacking and eddy diffusivity is unknown, recourse must be had to measurements of daily soil-moisture loss. Reliable studies of soil-water evaporation are rare because of the labor of taking the large number of soil samples required and the inherent variability of the findings. The most satisfactory for California are the 1921 field experiments by VEIHMEYER [1927] at Davis, Delhi, Mountain View, and Whittier reported in a companion paper [VEIHMEYER and BROOKS, in press]. At the end of April for the same convection conditions as in Veihmeyer's test plots the decreased evaporation based on Table 3 of the paper in press would be about half the July evaporation rate of 0.20 inch the first day. Considering the shading in a rather bare deciduous orchard, probably 0.08 inch is a fair estimate for 24-hour evaporation. The latent heat required for this about 400 Btu/ft^2.

Although convection of heat reverses at night, RICHARDS [1952] shows that the vapor-pressure gradient from moist surfaces in the soil is outward to air at night, even when dew is forming on foliage because the deeper levels of soil are warmer than the surface. Therefore, on a night with strong gravity air drift and low dewpoint, it is entirely within reason that surface evaporation should be 0.003 lb/hr ft^2 taking 30 Btu in ten hours, namely, less than a tenth the whole 24-hour loss. The seven-degree Fahrenheit evaporation chill following irrigation as shown in Figure 5 is, therefore, a wholly understandable response to the application of water in spite of the greatly increased daytime energy intake by the moistened soil.

Conclusions--Although careful measurements of microclimatological factors may sometimes seem erratic, inclusive study, even if elementary, of the 24-hour fluctuations in heat transfer by each of the four modes - radiation, conduction, convection, and evaporation - will reveal consistent explanations. By determining the relative magnitudes of heat flow by each of the four modes one can then estimate by the basic formulas for heat transfer the temperature deviations due to changing thermal conductivity and heat capacity of the soil (by adding water), or of changing eddy convection (by altering the wind velocity or the buoyancy stratification gradient), or of promoting evaporation (by wetting the soil surface). The sooner typical surface-transfer coefficients can be determined for a widening range of conditions, the easier will be a quick interpretation of the thermal characteristics which in fact describe the microclimatic environment. It is hoped that the condensed foregoing analyses utilizing measured radiation and conduction rates will increase confidence in interpreting microclimate. The thermal systems at each local spot may differ widely, but in a general area all are tied together by the same overhead meteorological conditions, and the net effect of all the four heat transfers at each spot is revealed by the soil temperature at that spot.

Acknowledgments--The two field projects reported necessarily involve many others, particularly C. E. Barbee, in charge of the Agricultural Engineering Research Laboratory, and Ralph Parks, Extension Agricultural Engineer, who planned and participated in the irrigation project. N. W. Stice, Farm Advisor for Lake County, helped in the field work at night and obtained the cooperation of D. Morrison, who very kindly made his orchard available for the irrigation tests.

APPENDIX--Symbols and units

A_o	Daily mean surface soil temperature (= 75° F, example 6/10/50), °F
C_{Hz}	Combined heat-capacity factor = $c_\gamma \alpha' f_s C_{tz}/C_{Uz}$, Btu/ft^3 °F
C'_{Hz}	Modified heat-capacity factor for offset between mean air and soil temperatures = $[1 + (A_o - t_{uo})/t_{sm}]\ C_{Hz}$, Btu/ft^3 °F
C_{tz}	Height factor for temperature gradient = $dt/dz/(t_s - t_{uo})$, (= 1/103, example 6/10/50), ft^{-1}
C_{Uz}	Height factor for velocity gradient = $dU/dz/U_o$, (= 1/165, example 6/10/50), ft^{-1}
c_p	Heat capacity, Btu/lb
c_γ	Average volumetric heat capacity = γc_p (= 29, example Feb., 1939) (= 15, example 6/10/50), Btu/ft^3 °F
E_{sm}	Maximum heat-conduction rate into the soil (= 70, example 6/10/50), Btu/hr ft^2
E_{um}	Maximum heat-convection rate into the air (= 147, example 6/10/50), Btu/hr ft^2
f_s	Wind friction coefficient (assumed 0.0008, example 6/10/50), non-dimen.
k	Average thermal conductivity (= 0.7 for soil, example Feb., 1939, and 0.5, example 6/10/50), Btu/hr ft^2/°F/ft
m_t	Coefficient of thermal turbulence (assumed 1.5, example 6/10/50), non-dimen.
t	Temperature, °F

t_{sm}	Amplitude of soil-surface temperature wave = $E_{sm}/\sqrt{kc_\gamma\omega}$, °F
t_{uo}	Average air temperature, °F
U_o	Mean wind velocity at standard height (= 59300, example 6/10/50), ft/hr
z	Height or depth, feet
$\sqrt{kc_\gamma\omega}$	Thermal admittance for semi-infinite slab ($\sqrt{kc_\gamma}$ = 2.7, example 6/10/50), Btu/hr ft^2/°F
α'	Ratio of heat to momentum eddy diffusivities (= 1.5, example 6/10/50), non-dimen.
γ	Weight density, lb/ft^3
θ_o	Full period based on daytime half-cycle time of positive net radiation (= 22 2/3 hr, example 6/10/50), hours
ω	Angular velocity of the cycle = $2\pi/\theta_o$, radians/hr

Subscripts

m	maximum, or mean
o	orchard trees, or reference standard
s	soil
t	turbulence, or temperature
u	air
U	mean velocity
z	height

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AN EXAMPLE OF A WAVE FORECAST BASED ON ENERGY SPECTRUM METHODS

Richard W. James

Abstract--A method is presented for wave forecasting based upon the energy spectrum of the wave system. Detailed descriptions of the forecasting graphs are given and the forecasting procedure explained. A numerical example, involving generation and decay of waves in an East Coast storm, is discussed.

Introduction--Oceanographers have long realized that single-valued wave height and period forecasts are unrealistic when compared with observed waves. Wave records show that a wave train in a fetch is not a simple sine wave of single period and constant amplitude, but rather a combination of many different waves of various heights and periods.

Empirical and theoretical forecasting methods based on single-valued observations and the assumption of a single sine wave in the generating area are necessarily incomplete. A more realistic approach to the problem of wave forecasting is one involving study of the wave spectrum.

Some studies have been done along this line such as those by DEACON [1949], BARBER and URSELL [1948], and, more lately, PIERSON [1952] and NEUMANN [1952]. The present paper is based on the latter two works.

General theory--The complex sea surface can be approximated by the sum of an infinite number of sine waves of infinitesimally small amplitude added in random phase. This has been shown theoretically by PIERSON [1952], and observations verify this property to a close approximation.

Thus the sea surface can be represented by a spectrum, showing the energy of the various frequency components. When the wind blows over the water, a characteristic spectrum develops, the extent of which depends upon the fetch length and the wind parameters of velocity and duration. NEUMANN [in press] has shown that the total energy present in a wave train can be represented by an energy spectrum which relates wave energy to wave frequency for a given wind velocity.

Figure 1 [see also NEUMANN, in press, Fig. 10c] gives co-cumulative spectra, actually the energy spectrum integrated from a particular frequency to infinity, for wind speeds from 36 to 56 knots. The spectrum grows as a function of frequency from high frequencies to low frequencies. An intersection of a duration line with a CCS curve determines the lowest frequency present, the total area under the energy spectrum for that duration, and the energy in any frequency band. This graph is presented as a function of duration but the same curves can be given as a function of fetch length, similar to those of Figure 4 [see also NEUMANN, in press, Fig. 11b].

Since the spectrum grows from the low-period end of the spectrum toward the high-period end, the area under the CCS curve for a given velocity is a measure of the energy in the wave train. As the duration of a given wind velocity increases over a long enough fetch the E value increases until a limiting value is reached, at which point no further energy can be added to the wave train. The sea at this point is called a fully developed sea, which means that all periods and heights maintained by that particular wind are present.

The quantity E is equal to the sum of the square of the individual sinusoidal amplitudes in the total spectrum. Since the wave system is approximately Gaussian, an approximate relationship between E and the average height, the significant height, or any required height can be determined from the theoretical work of LONGUET-HIGGINS [1952].

According to LONGUET-HIGGINS [1952] this relationship results in the following values

$$\bar{H} = \text{average height} = 1.77\sqrt{E}$$
$$\bar{H}_{1/3} = \text{significant height} = 2.83\sqrt{E}$$
$$\bar{H}_{1/10} = \text{average 1/10 height} = 3.60\sqrt{E}$$

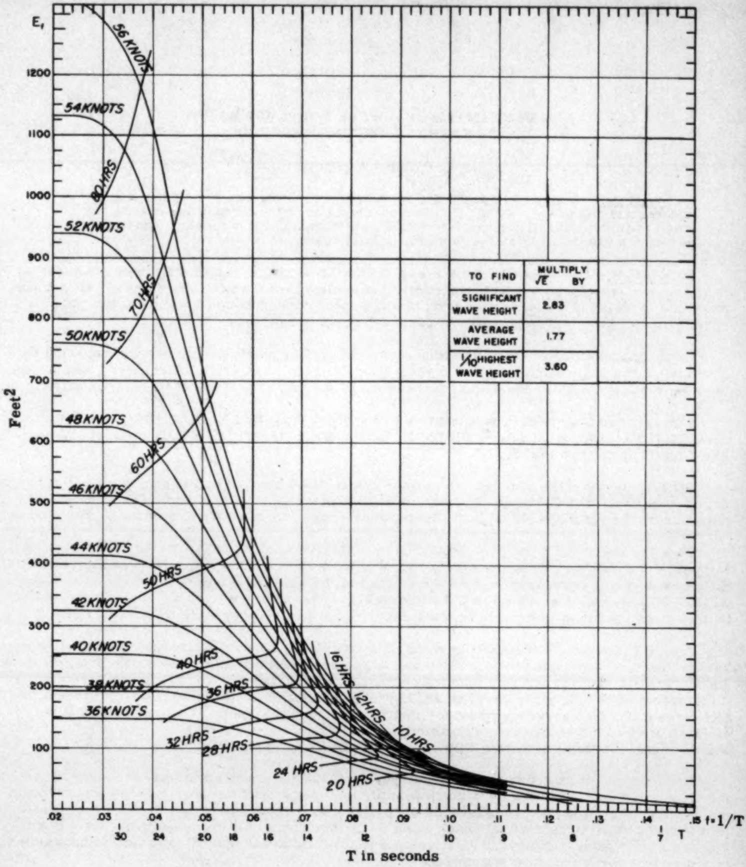


Fig. 1--Duration graph co-cumulative spectra for wind speeds from 36 to 56 knots as a function of duration

A more complete discussion of the above theory can be found in a manual on wave forecasting by PIERSON, NEUMANN, and JAMES [1953].

Forecasting procedure for wave generation--Once the wind field has been established, the procedure for a wave forecast in the generating area is as follows:

(1) Enter the proper graph (duration or fetch, whichever gives the lowest E value) and read off the E value at the intersection of the velocity line with the fetch or duration line.

(2) Take the square root of E and multiply it by 2.83 to get the significant height, or by the other factors to get the average height or the average height of the 1/10 highest waves.

(3) The period band present consists of all periods to the right of the point of intersection. Since the energy contributed by periods at the end of the band is negligible (as far as stop-watch visual observations are concerned), use only the period band between 0.95E and 0.03E, not the entire E value.

The period range is presented in the final forecast but the frequency is used with the graphs as the latter is easier and more accurate to work with. Thus, in Figure 1, for a fully developed sea at 36 knots, the actual frequency band is from 0.040 to infinity theoretically (0 to 24 sec), but taking 0.95E and 0.03E (equal to 150 here) results in values of E equal to 142 and 4.5 which then intersects the 36-knot curve at a frequency of 0.053 (19 sec) and 0.15 (7 sec). The effective period range is then seven to 19 sec. Actually, the time intervals between successive crests are meant here and not the period in a mathematical sense.

The average period for a fully developed sea is found from the formula

$$\tilde{T} = 0.285v \quad \ldots\ldots\ldots\ldots \quad (1)$$

where v is the wind velocity in knots.

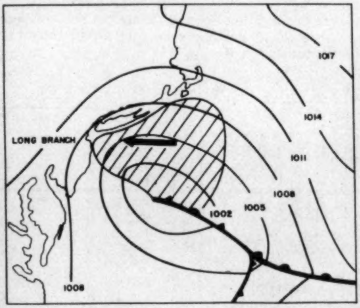


Fig. 2--Storm of May 5, 1948, at 20h 00m EST

A sample wave forecast--On May 4, 1948, a low-pressure area was located on the East Coast of the United States with a warm front extending from Hatteras to Bermuda. During the afternoon, a secondary low developed on the front and subsequently intensified into a mature East Coast storm. Figure 2 shows the general weather picture at 20h 00m EST on May 5, 1948, when the waves reached their maximum height. Long Branch, N. J., was selected as the forecast point as wave observations were available at four-hour intervals for that station.

From ship and coastal station reports, the following wind velocities were determined: May 5, 04h 00m EST, 16 knots 6-hr duration, ESE; May 5, 12h 00m EST, 20 knots 8-hr duration, ESE; May 5, 20h 00m EST, 24 knots 8-hr duration, E.

The first forecast was made for 04h 00m EST on May 5 and depended upon the duration graph similar to Figure 1 [NEUMANN, in press, Fig. 10a]. Using wind values of 16 knots and six hours, an E value of 2.62 was found and a frequency band from 0.32 to 0.10. This includes the full curve and indicates that the sea was fully developed.

Table 1--Forecast heights at 04h 00m EST, May 5, 1948

Group	Value	Height ft
$\bar{H}$	$\sqrt{E} \times 1.77$	2.9
$\bar{H}_{1/3}$	$\sqrt{E} \times 2.83$	4.6
$\bar{H}_{1/10}$	$\sqrt{E} \times 3.60$	5.8

Table 2--Forecast heights at 20h 00m EST, May 5, 1948

Group	Value	Height ft
$\bar{H}$	$\sqrt{E} \times 1.77$	7.9
$\bar{H}_{1/3}$	$\sqrt{E} \times 2.83$	12.5
$\bar{H}_{1/10}$	$\sqrt{E} \times 3.60$	16.0

Table 1 gives the forecast heights computed from the E value of 2.62 ft^2. Reduction of the frequency band resulted in a period forecast of three to nine seconds. The forecast average period was 4.5 sec as computed from (1).

The second forecast was made for the most intense part of the storm, which occurred at 20h 00m EST, May 5. The wind velocity at that time was 24 knots with an eight-hour duration. In this forecast, allowance had to be made for the waves already present in the generating area. The wave height is not necessary, only the power spectrum at the time when the stronger winds began. Since there was a 20-knot wind at 12h 00m EST which had been blowing long enough to produce a fully developed sea for that velocity, the E value was 8 (as determined from a graph similar to Figure 1 [see NEUMANN, in press, Fig. 10b]. From this same graph it is evident that a 24-knot wind would require nine hours to reach that particular E value, so the duration must be increased by nine hours.

With a 17-hr duration, a 24-knot wind produces a fully developed sea with an E value of 19.7. The forecast heights are given in Table 2. The corrected frequency or forecast period range was three to 13 sec, and the forecast average period was 6.8 sec.

Sixteen hours later, at 12h 00m May 6, the wind had decreased to 16 knots. That was the same velocity as had occurred at 04h 00m May 5, before the storm, and since all spectral components from the peak of the storm had disappeared by that time the forecasts were identical.

Although the local wind and waves had decreased by 12h 00m May 6, there was a well-developed fetch area 125 mi offshore which was to cause a slight wave increase in the following 12 hr. This brings up the problem of wave propagation and a more complicated procedure.

Wave propagation--The basic procedure for wave propagation is to calculate the power spectrum in the fetch area and then apply a filter which involves an angular spreading factor and a dispersion effect to determine the power spectrum at the forecast point.

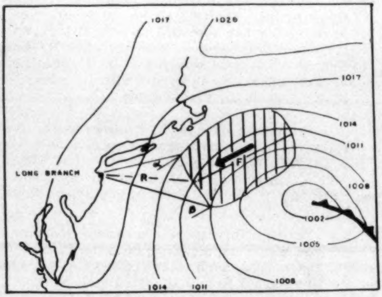


Fig. 3--Decay distance, fetch area, and angles of spreading for storm at 12h 00m EST, May 6, 1948

Figure 3 pictures the fetch area at 12h 00m EST, May 6, the distance of decay R, and the two angles α and β needed for the angular spreading factor. The storm moved northward after this map, cutting off the wind. This is a filter III storm, as defined in PIERSON, NEUMANN, and JAMES [1953].

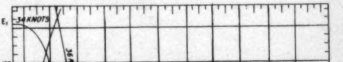


Fig. 4--Co-cumulative spectra for wind speeds from 20 to 36 knots as a function of fetch

The wind field in the fetch area was 24 knots with a 14-hr duration over a 110-nautical mile (nm) fetch. The fetch length was short enough here to be the limiting factor so that the fetch generation graph, Figure 4 [see also NEUMANN, in press, Fig. 11b], was used.

The first step is to find the lowest frequency (highest period) present in the fetch area and compute the travel time to the point of forecast. The lowest frequency in the fetch area was found from Figure 4 to be 0.09. This is the point of intersection of the 24-knot velocity curve and the

110-mi fetch. The frequencies present are found for a given travel time by use of the dispersion diagram, Figure 5, which relates decay distance R to frequency and travel time. For this forecast, f was 0.09 and R equaled 100 nm, so that the travel time was found to be six hours. That is, no waves from that particular fetch would arrive at Long Branch for six hours, or until 18h 00m EST, May 6.

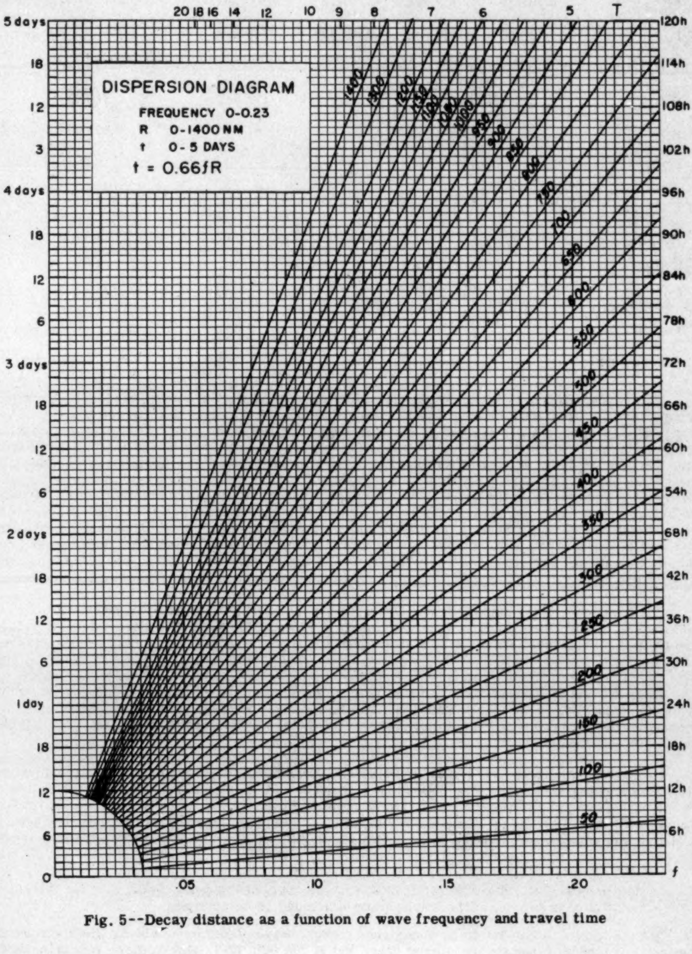


Fig. 5--Decay distance as a function of wave frequency and travel time

Table 3--Calculations for wave propagation

	Forecast for		
	8 hr (20h 00m EST May 6)	12 hr (24h 00m EST May 6)	16 hr (04h 00m EST May 6)
f_1	0.120 8.2 sec	0.183 5.6 sec	0.240 4.2 sec
f_2	0.060 11.0 sec	0.090 11.0 sec	0.118 8.8 sec
E (f_1)	10.0 ft^2	4.5 ft^2	1.0 ft^2
E (f_2)	16.0 ft^2	16.0 ft^2	11.0 ft^2
E	6.0 ft^2	11.5 ft^2	10.0 ft^2
0.20E	1.2 ft^2	2.3 ft^2	2.0 ft^2
. . . . (local)	1.3 ft^2	. . . . .	. . . . .
$\overline{H}$	2.8 ft	2.7 ft	2.5 ft
$\overline{H}_{1/3}$	4.6 ft	4.3 ft	4.0 ft
$\overline{H}_{1/10}$	5.8 ft	5.4 ft	5.1 ft
Period range	2-8 8-0	5-11 sec	4-8.8 sec
Average period	4.0 sec	8.0 sec	6.3 sec

The second step is to set up a table in which the energy present at the forecast point at four-hour intervals after 18h 00m May 6 is calculated. Since the observations are for 20h 00m, 24h 00m, etc., the first forecast was started at 20h 00m instead of 18h 00m. Table 3 shows the computations for this example, and a step-by-step description follows. Lines 1 and 2 give the band of frequencies present at Long Branch after 8, 12, and 16 hr travel time. The frequencies, f_1, were obtained by entering Figure 5, with t of 8, 12, and 16 hr as travel time and R of 100 nm. The second line was based on the same travel times, but now R was the distance from the back of storm, or 210 nm. Naturally the greater distance means that a smaller frequency will be obtained for f_2 at a given time. At a given time of forecast the energy associated with all frequencies less than f_2 has already passed the point of observation, and the energy associated with all frequencies greater than f_1 has not yet arrived. Thus only the spectral energy between f_2 and f_1 can be present at the time of the forecast.

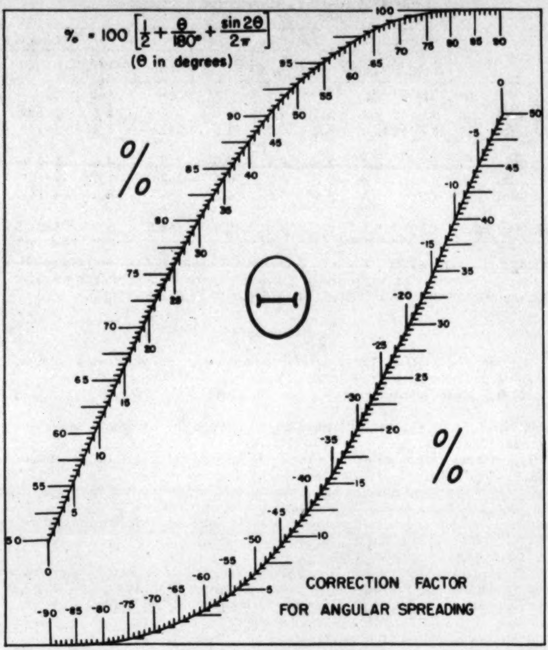
The next three lines represent the E values present at the forecast point and are obtained by subtracting the E value for f_1 at 24 knots from the E value for f_2 at 24 knots. These E values can be determined from Figure 4 by rising vertically from the given frequency to intersect the 24-knot line.

The next line is the angular spreading factor. It is computed by a diagram, Figure 6, which is based on the angles α and β pictured in Figure 3. As can be seen from the figure, α and β are the angles between the wind direction in the fetch and lines to the forecasting point drawn from the corners of the fetch.

In this example, α is -19° and β is -44° which gives 30 and ten per cent, respectively, from the angular spreading diagram. The angles are entered on the inside and the per cent values are read on the outside of the curves. The actual value applied is the difference between these two values, which is 20 pct. Thus 20 pct of the energy between f_1 and f_2 in the spectrum in the fetch area will arrive at the selected forecasting point, and the rest will spread out angularly and arrive at other points.

At this point the E value associated with the spectrum at the point of forecast for the selected forecasting times is known, so the height distribution can be computed.

One additional factor has to be considered though: waves from local winds. The local winds at the last two forecast times were almost calm, but at 20h 00m EST, May 6, there was a 14-knot SE wind blowing.


$\% = 100 \left[\frac{1}{2} + \frac{\theta}{180^\circ} + \frac{\sin 2\theta}{2\pi}\right]$
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CORRECTION FACTOR
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Fig. 6--Angular spreading diagram

The procedure in the case of two-wave systems is simply to add their power spectra and widen the period range to include both systems. A 14-knot wind has an E value of 1.30 over a band of two to eight seconds, so the total E for the first column is 2.50. The remaining lines present the final height and period forecast at Long Branch for the three forecasting times.

Verification--Wave records from a step-resistance-type wave gage, as installed and operated by the Beach Erosion Board, were used to verify the forecasts for Long Branch. This type of instrument was preferred over the pressure recorder as the latter fails to record all the higher frequencies.

Frequency distributions were made of both height and periods from the observations. Each wave record was seven minutes long and the samples ranged from 50 to 100 individual waves. Table 4 summarizes the forecast and observed values for this example.

All height forecasts agreed favorably with the observations in timing and magnitude. The forecast heights were high at the peak of the storm, but this can be explained in part by shallow water effects on the observed values. On the basis of the number of individual waves in the records used to verify the forecasts, the verification is excellent as shown by PIERSON, NEUMANN, and JAMES [1953].

Table 4--Forecast and observed wave values

Date	Time	Forecast height			Observed height			Forecast period		Observed period	
		$\bar{H}$	$\bar{H}_{1/3}$	$\bar{H}_{1/10}$	$\bar{H}$	$\bar{H}_{1/3}$	$\bar{H}_{1/10}$	Range	Average	Range	Average
		ft	ft	ft	ft	ft	ft	sec	sec	sec	sec
May 5	04h 00m	2.9	4.6	5.8	3.1	4.5	5.8	3-8.8	4.5	2-8.0	4.0
	20h 00m	7.9	12.5	16.0	5.9	10.0	14.0	3-13	6.8	3-11	6.6
May 6	12h 00m	2.9	4.6	5.8	2.9	4.4	5.6	3-8.8	4.5	2-9.0	4.6
	20h 00m	2.8	4.6	5.8	2.9	4.9	6.1	2-8.0	4.0	2-10	5.0
	24h 00m	2.7	4.3	5.4	2.5	3.6	4.2	5-11	8.0	4-11	6.9
May 7	04h 00m	2.5	4.0	5.1	2.4	4.0	5.0	4-8.8	6.3	4-9	5.9

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PROBLEMS CONNECTED WITH THE COOLING OF THE EARTH

J. A. Jacobs

Abstract--The composition of the Earth's core is reviewed and a physical explanation is offered as to how the Earth's inner core may have become solid. The question of convection currents in the Earth's core is examined and it is estimated that convection can arise if the radioactive content of the inner core is only about two per cent of that in the crust. Finally it is shown that conduction alone will probably suffice to transfer the heat from the core through the surrounding mantle.

Introduction--In recent years it has been suggested by some authors that the Earth's core does not consist of iron. Thus KUHN and RITTMANN [1941] consider the whole of the interior of the Earth to consist of undifferentiated solar matter whose main constituent is hydrogen. This hypothesis, however, has received severe criticism from many authors. An account of their arguments has been given in a review by ELSASSER [1950a] and the question will not be discussed further here. More recently RAMSEY [1948, 1949] has put forward the hypothesis that the Earth consists of a homogeneous material having essentially the composition of the mantle, that is, a simple magnesium iron silicate such as olivine. He regards the boundary between the core and the mantle as merely representing a phase change in the material, the material in the core being a metallic phase of the silicates. Although attractive in many ways, it now seems most probable that Ramsey's hypothesis is untenable. His theory was originally designed to reconcile the densities of the inner planets with the present views on the origin of the solar system. The latest values of the masses of Mercury and Venus, however, conflict with his theory [KUIPER, 1952]. Apart from objections on astronomical grounds, Ramsey's hypothesis also conflicts with data on the Earth interpreted in the light of theoretical physics [see, for example, ELSASSER, 1950a, 1951]. We thus adopt the older idea that the Earth's core consists of iron, or, to be more precise, of an iron nickel alloy similar to that found in iron meteorites.

The inner core--All seismic work indicates that at least part of the core of the Earth is liquid, since no transverse waves have ever been observed to pass through it. It has been suggested, however, that the core contains an inner core beginning at a depth of approximately 5000 km which is solid. BULLEN [1947] has shown that the rise in velocity of longitudinal waves at this depth can be explained by assuming it to be solid and of the same composition as the rest of the core. The following argument gives a possible physical explanation as to how the inner core could have become solid.

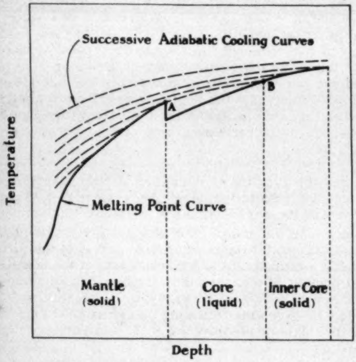

Fig. 1--Melting-point curve of the Earth's interior

Most theories of the origin of the Earth agree that it passed through a molten stage before finally separating into the different layers. URRY [1949] has shown that even an Earth formed from the cold accretion of dust particles would melt by the accumulation of heat from radioactive elements, and subsequently solidify as the amount of radioactive material decreased with increasing age of the Earth. The work of UFFEN [1952], based on seismic data and the theory of solids, has shown that the melting-point gradient in the mantle is considerably less than the theoretical curve proposed by JEFFREYS [1952]. At the boundary between the core and the mantle, there will be a discontinuity, and it is assumed that the melting point of the material in the iron core is less than that in the silicate mantle. (Note added in proof: This assumption has now been proved). The melting-point curve is thus likely to have the general shape shown in Figure 1.

As the Earth cooled from its molten state, the temperature gradient would be essentially the adiabatic, there being strong convection currents and rapid cooling at the surface. Solidification would commence at that depth at which the curve representing the adiabatic temperature first intersected the curve representing the melting-point temperature. It is suggested, therefore, that solidification began at the center of the Earth, and not at the boundary of the core and mantle as is at present supposed. A solid inner core would continue to grow until a curve representing the adiabatic temperature intersected the melting-point curve twice, once at A, the boundary of the core and mantle, and again at B, as shown in Figure 1. As the Earth cooled still further, the mantle would begin to solidify from the bottom upwards. The liquid layer between A and B would thus be trapped. The mantle would cool at a relatively rapid rate, leaving this liquid layer essentially at its original temperature, insulated above by a rapidly thickening shell of silicates and below by the already solid (iron) inner core. It is interesting to note that ADAMS [1924] showed nearly 30 years ago that the intersections of the melting-point depth curve and the curves representing adiabatic convective equilibrium at various epochs in the cooling of the Earth would determine the nature of the Earth's solidification.

In this argument no specific values of temperature are postulated, and the precise behavior of both the adiabatic and melting-point curves is immaterial. Should more accurate data indicate, however, that the curves do not vary qualitatively as shown and so invalidate the above reasoning, it would not affect the rest of this paper which is independent of this section.

Motions in the Earth's core--The geomagnetic secular variation can be interpreted as the result of motions in the fluid electrically conducting core, and ELSASSER [1950b] has shown that thermal convection provides the only satisfactory mechanism for the generation of such motions. Apart from the production of sufficient heat flow to maintain these convection currents, there is the added difficulty of the removal of heat from outside of the core. These questions are now examined in more detail using the results of the recent investigations of JACOBS [1953] and UFFEN [1952].

The conductive heat flow q is calculated from the relation $q = k\tau$, where k is the conductivity and τ the temperature gradient. Following BULLARD [1950] and ELSASSER [1950b] we take the value of k in the liquid iron core to be 0.18 cal/cm sec deg. Since the core is in a state of convective agitation, the temperature gradient will be the adiabatic. The adiabatic temperature gradient in the core has recently been estimated by JACOBS [1953] who obtained the values $\tau = 0.30$ deg/km at the boundary between the core and mantle, and $\tau = 0.10$ deg/km at the boundary of the inner core, (that is, at a depth of approximately 5000 km). Thus the conductive heat flow at the boundary of the inner core is 1.8×10^{-7} cal/cm^2 sec. Thermal convection will occur in the core if the transport of heat radially outwards due to the physical conditions that prevail there exceeds the heat transport by thermal conduction alone. If the heat flow Q at the boundary of the inner core exceeds 1.8×10^{-7} cal/cm^2 sec, convection currents will be set up. Let us suppose, for instance, that Q is double this amount, that is, 3.6×10^{-7} cal/cm^2 sec, and compare this figure with the radioactive heat developed in the Earth's crust. A large part of the heat flow in the crust is due to radioactivity, so that the measured mean heat outflow from the crust, namely, 1.3×10^{-6} cal/cm^2 sec [BIRCH, 1942] should be representative of the order of magnitude of the radioactive heat developed in the crust. This is about 3 1/2 times the value of Q. Since the surface area of the inner core is only about five per cent of that of the crust, the radioactive content of the inner core need be less than two per cent of that in the crust. BULLARD [1950] found that the heat flow required to maintain convection currents was about four times greater than that available from a core with a radioactive content comparable to that of iron meteorites. This discrepancy is now removed if the results of the above investigation are used.

Transfer of heat from the core--We now consider the question of the removal of heat from the core. At the boundary between the core and mantle, the adiabatic temperature gradient is 0.30 deg/km, so that the conductive heat flow at a point just inside the core is $(0.30) \times (0.18)\ 10^{-5}$ cal/cm^2 sec, that is, 5.4×10^{-7} cal/cm^2 sec. At a point just inside the mantle, the temperature gradient is not likely to differ much from the melting-point gradient, whilst the conductivity is that of the silicates composing the mantle. Little is known about the melting point and conductivity of these silicates such as olivine at the extreme pressures that prevail at these depths. Rather than extrapolate from laboratory conditions, we make use of the recent values of UFFEN [1952], which are again based on seismic data and the theory of solids. He gives the following values at 2900 km: τ = melting-point gradient = 8×10^{-6} deg/cm; k = thermal conductivity = 6×10^{-2} cal/cm sec deg. Hence the conductive heat flow = 4.8×10^{-7} cal/cm^2 sec.

Thus about 90 pct of the heat flow in the core at the boundary between the core and mantle can be carried away by conduction. In fact, the slight difference in conductive heat flow on opposite sides of the boundary between the core and mantle is insignificant as the approximations in the general theory do not warrant giving a numerical result to within ten per cent. The main point is that the conductive heat flows are of the same order of magnitude and it thus appears that sufficient heat can be removed from the core by conduction alone, a result not hitherto thought possible. Thus in order to have convection currents in the core to account for the Earth's magnetic field, it is not necessary to have convection in the mantle as well.

The above argument does not establish that convection in the mantle does not exist, but it does show that it is not necessary in order to have convection in the core. This result lends considerable weight to the contraction theory of orogenesis first proposed by Davison, Darwin, and Jeffreys, and more recently examined by SCHEIDEGGER and WILSON [1950] and SCHEIDEGGER [1952] as against the convection-current hypothesis.

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REPORT OF THE COMMITTEE ON EVAPORATION AND TRANSPIRATION, 1952-1953

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Harry F. Blaney	E. G. Dunford	John R. Mather
Carl Rohwer	Richard B. Marston	Paul J. Kramer

J. R. Mather (Laboratory of Climatology, Johns Hopkins University, Seabrook, N. J.)--Comparison of values of potential evapotranspiration measured by the six evapotranspirometer tanks [1951-1952 Committee Report, Trans., v. 34, pp. 625-627, 1953] in use at Seabrook, New Jersey, since June, 1948, with values computed from climatic data by Thornthwaite's empirical expression, have shown that the formula underestimates evapotranspiration during cold periods and overestimates it during warm periods. Efforts have been made to establish evapotranspirometers in other climatic regions to permit further testing of the results found at Seabrook. In 1951 a simplified version of the Thornthwaite evapotranspirometer was designed [J. R. Mather, Design and evaluation of a modified evapotranspirometer, Johns Hopkins Univ., Lab. of Climatology, Interim Report 15, 1951, pp. 11-15]. It is inexpensive to build and can be operated by unskilled personnel. Use of the simplified evapotranspirometer will permit the installation of a number of additional observing stations.

Evapotranspirometer installations which are now or have been in operation are listed in Table 1 along with the length of record available in each case. Most of the records have been published.

Table 1--Location, number, and length of record of evapotranspirometers

Location	Number in operation	Length of record
Seabrook, N. J.	1	Aug. 24, 1947-Nov. 9, 1947
Seabrook, N. J.	6	June 8, 1948-present
Seabrook, N. J.	1 (simplified)[a]	July 10, 1951-present
Norman Wells, N. W. T.	2	July 2, 1949-Sept. 1, 1949
Norman Wells, N. W. T.	2	June 12, 1950-Sept. 7, 1950
Toronto, Ontario	4	June 25, 1947-Nov. 14, 1947
Toronto, Ontario	4	June 13, 1948-Nov. 30, 1948
Toronto, Ontario	4	May 2, 1949-Nov. 22, 1949
Orono, Ontario	2 (shaded)	June 16, 1948-Sept. 22, 1948
Orono, Ontario	2	May 27, 1949-Sept. 14, 1949
Hong Kong	3	Oct. 1, 1951-present
El Mante, Tamaulipas, Mexico	2	Nov. 22, 1950-Nov. 21, 1951
University College, Ibadan, Nigeria	2 (simplified)[a]	June 1, 1951-present
Moor Plantation, Ibadan, Nigeria	1 (simplified)[a]	June 1, 1952-present
Port Harcourt, Nigeria	1 (simplified)[a]	June 1, 1952-present
Samaru, Nigeria	1 (simplified)[a]	June 8, 1952-present
Daura, Nigeria	1 (simplified)[a]	July 19, 1952-present
Trinidad, B. W. I.	4	Oct. 1, 1952-present
Valentia, Ireland	4	July 20, 1952-present

[a] Simplified evapotranspirometers are approximately 0.25 sq m in surface area. All others are about 4 sq m in area.

The records from most of these installations are still too short to be useful in determining a possible modification of the Thornthwaite formula. Preliminary analysis of the data received shows that a seasonal bias in the comparison of measured and computed evapotranspiration is found in other localities. However, instead of being related to temperature as is apparent at Seabrook, evaporation appears to be related to moisture also, and possibly to other factors, in the tropical and subtropical regions. The possibility of the inclusion of a moisture term in the Thornthwaite empirical evapotranspiration expression is being studied.

Evapotranspirometers will be installed also in the following localities: La Lima, Honduras; San Martin, Mendoza, Argentina; Osaka, Japan; and at a site to be determined in Israel. In addition it is thought that the records from other soil tanks such as the ones at Zerafcut, Sudan; Victorville, California; and Belle Glade, Florida, which have been operated somewhat like evapotranspirometers, can be used to give more information on the geographical distribution of potential evapotranspiration. Every effort is being made to uncover more of these useful records. Many records of evapotranspiration from soil tanks are of little use because of limitations which result from exposure or operation of the soil tank itself. Thus the records must be carefully evaluated before being accepted for testing purposes.

Nedavia Bethlamy (Northeastern Forest Experiment Station, Forest Service, Upper Darby, Pa.)--Studies at the Delaware-Lehigh Experimental Forest in northeastern Pennsylvania suggest a simplified method for determining evapotranspiration. Daily soil-moisture losses were analyzed for periods during the summer months and the losses related to several climatic and soil factors. Atmospheric saturation deficit was the only climatic element statistically related to evapotranspiration loss. Analysis revealed this to be a logarithmic relationship and that the relationship exists only at saturation deficits larger than 0.02 inch of mercury. Further analysis revealed that the regression coefficients obtained in relating evapotranspiration losses to saturation deficit were related also to the total sand content in the soil profile by a direct straight-line regression.

The existence of these interesting relationships which link evapotranspiration losses, saturation deficit, and sand content of the soil suggest the possibility of determining evapotranspiration losses by making a mechanical analysis of the soil and determining atmospheric saturation deficit. Since the experiment was done on a watershed where an attempt is being made to balance the water economy, it was possible to make a rough check of the calculated evapotranspiration losses. The check was favorable. The relationship is being explored further to determine its application to soils of higher and lower sand content.

Harry F. Blaney (Soil Conservation Service, U. S. Department of Agriculture, Los Angeles, Calif.)--In connection with studies of evaporation losses from reservoirs used for irrigation, municipal, and power purposes, the Division of Irrigation Engineering and Water Conservation has been cooperating with the Southern California Edison Company for a number of years at evaporation stations established at high elevations in the Sierra Nevada Mountains, Fresno County, California. The results for 1951 are shown in Table 2. Examples of some of the reports released by the Division on consumptive use (evapotranspiration) during 1952-1953 are as follows: Harry F. Blaney and Karl Harris, Consumptive use and irrigation requirements of crops in Arizona, SCS, USDA, 49 pp., December, 1951; Harry F. Blaney, Evapotranspiration by vegetative cover with particular reference to semi-arid areas, Sixth Internat. Grassland Congress, August, 1952; Harry F. Blaney

Table 2--Evaporation-loss data for 1951

Month	Huntington Lake[a] evaporation (elev 6954 ft)		Florence Lake[b] evaporation (elev 7345 ft)		Shaver Lake[c] evaporation (elev 5376 ft)		Kaiser Pass[d] evaporation (elev 9194 ft)	
	Weather Bureau pan	Young screen pan	Weather Bureau pan	Young screen pan	Weather Bureau pan	Young screen pan	Weather Bureau pan	Young screen pan
1951	inch	inch	inch	inch	inch	inch	inch	inch
May	3.14	2.31	2.07	1.57	3.63	2.68	. . .	. . .
June	6.91	5.13	7.46	5.27	7.78	6.14	5.13	3.53
July	8.05	5.80	8.54	6.73	9.31	7.89	8.38	5.85
Aug.	7.80	6.21	8.13	6.56	8.73	7.58	8.13	6.43
Sept.	6.15	4.77	7.05	5.82	6.60	5.56	6.33	4.25
Oct.	2.43	1.95	2.47	1.87	3.76	3.37	. . .	. . .
Nov.	. . .	. . .	. . .	. . .	1.36	1.05	. . .	. . .

[a] May 17 to October 19, 1951.
[c] May 16 to November 19, 1951.
(pans frozen other months).
[b] May 24 to October 16, 1951.
[d] June 9 to September 30, 1951.

and Karl Harris, Consumptive use of water rates in the Lower Colorado River basin, SCS provisional report to Bur. Reclam., 88 pp., March, 1952; Willis C. Barrett and Cleve H. Milligan, Consumptive water use and requirements in the Colorado River area of Utah, Spec. Rep. 8, Utah Agri. Exp. Sta., 28 pp., March, 1953.

R. B. Marston (Intermountain Forest and Range Experiment Station, U. S. Forest Service, Ogden, Utah)--Studies to determine the effect of different plant-cover types in situ on water available for stream flow have been made in recent years in northern Utah. Methods and comparative results from an aspen-herbaceous type, an herbaceous type, and from bare soil were given in the 1951-1952 report of this Committee in the August, 1953, Transactions. In the fall of 1951, these studies were extended by preliminary investigations of the soil-moisture deficit under dense grass and sparse weed subtypes within the herbaceous type. Eight test holes were dug in each of these two subtypes and soil-moisture samples were obtained foot by foot to five feet deep. These samples exhibited a 1.25-inch greater deficit under dense grass than under sparse weeds. This difference was statistically significant. Foot by foot the differences were significant in the second and third feet, but were not significant in the first, fourth, and fifth feet, as shown in Table 3.

Table 3--Water content of soil mantle under sparse weeds and dense grass, Davis County experimental watersheds, 1951

Subtype	Water content for various depths of sample						
	0-12	12-24	24-36	36-48	48-60	0-36	0-60
	inch	inch	inch	inch	inch	inch	inch
Sparse weeds	1.016	1.270	1.559	1.679	1.606	3.84	7.13
Dense grass	0.846	0.912	1.136	1.460	1.528	2.89	5.88
Difference	0.17	0.36[b]	0.42[a]	0.22	0.08	0.95[b]	1.25[a]

[a] Significant, statistically. [b] Highly significant, statistically.

This exploratory study suggests that sparse stands of annual weeds in the test area may provide only about one inch more water for seepage to stream flow than a vigorous stand of perennial grass. The well-known inferiority of annual weed cover as range forage and as protection against soil erosion and destructive storm runoff eliminates consideration of its use as a means of increasing water yields on steep mountain lands. Further study is now under way aimed at finding perennial forage plants which will consume the least water and at the same time provide adequate control of storm runoff and soil stability.

Marvin D. Hoover (Piedmont Research Center of Southeastern Forest Experiment Station, Asheville, N. C.)--Measurements of soil moisture under various types of plant cover were started at Union, South Carolina, in 1950. Colman fiberglas units were installed to a depth of 72 inches under 10-12 years old planted loblolly pine, 30-40 years natural shortleaf pine, broom sedge, and on two sites without vegetation. In addition to Colman block readings, soil samples were taken with a soil tube and moisture content determined by oven drying. Rainfall is measured at all sites and interception by the plant canopy is measured at the forested sites. Precipitation was considerably below normal in 1950 and 1951 but about average in 1952.

The most significant finding is the depth to which pine roots withdraw moisture. In each of the three growing seasons, the soil at the six-foot depth has been at or very near the wilting point under tree cover while at broom sedge sites there is little moisture removed below depths of 36 inches. On barren sites, evaporation has not dried the soil to the wilting point at depths greater than 24 inches.

Because of the greater rooting depth of pines the combined evaporation-transpiration loss was about five inches larger during the growing season in 1952 for pine forest than for a broom sedge field. Results of the interception study in planted loblolly pine are published as Station Paper 21 of the Southeastern Forest Experiment Station. Seasonal soil-moisture changes were reported at the 1952 meeting of the Soil Science Society of America and were submitted for publication in the Proceedings.

The results of this work emphasize the need to learn more about depth of rooting on various sites for, at least, the common forest trees. Measurement of annual leaf fall in various forest types indicate that foliage is remarkably constant for a wide range of stand densities and species compositions indicating that the variable leaf area, which has proven so useful in the laboratory for comparison of transpiration rates, may be useless in studying transpiration on an area basis. Differences in the depth of rooting, by its direct effect on water available for transpiration, appears to be the most important variable for use in determining or estimating transpiration under natural conditions in the field.

The effect of depth of rooting as it influences moisture supply must be considered in all calculations of transpiration based on energy relationships. Another factor which also deserves more consideration than it has been given is the possible difference in absorption of radiant energy by leaves of different species. Even under the same conditions of exposure and with equal surface presented, it appears probable that absorption of radiant energy may differ by ten to 20 pct between species.

Paul J. Kramer (Department of Botany, Duke University, Durham, N. C.)--Present-day views regarding transpiration raise serious questions concerning the usefulness of studies on potted plants. In the earlier work attention was centered on plant factors such as stomatal behavior, differences in rates among species, and the transpiration ratio of various crops, all of which could be studied with potted plants. The present trend, as exemplified by the work of Thornthwaite and Penman, is to regard transpiration as a physical process controlled largely by the supply of solar energy available for evaporation of water from plant surfaces.

Penman and Schofield, for example, in calculating evaporation from plant cover treat the vegetation as a single plane surface. According to this view of transpiration, if soil moisture is not limiting and if there are no differences in depth of root penetration, the type of plant cover should have no effect on the amount of evapotranspiration from a given area. This has been demonstrated to be true under experimental conditions and it has led some writers to conclude that measurements of water loss from potted plants or parts of plants cannot be related in any way to water loss from an area of vegetation and are therefore useless.

There seem to be serious limitations also on the general application of the energy concept to water loss except in regions of uniformly high rainfall and rather shallow soils. Differences in depth of rooting are common, both among crop plants and in natural vegetation. Hoover (in this report) and others have shown how depth of rooting affects water loss. Furthermore, in most of the United States soil moisture becomes a limiting factor one or more times during almost every growing season. It seems unlikely that the transpiration rates of different species are reduced to the same extent as soil moisture decreases. It also seems possible that besides the differences in absorption of energy by individual leaves mentioned by Hoover, there may be differences in absorption of energy by different stands. For example, an open stand of conifers with its irregular surface might absorb more solar radiation and lose more water than a closed stand with a relatively smooth topped canopy.

Even though results of pot experiments cannot be applied reliably to the estimation of transpiration from land areas, they do provide certain kinds of information obtainable in no other way. Pot experiments are particularly useful for measuring differences in effects of such factors as soil temperature, soil-moisture deficits, and mineral nutrition on transpiration of various species. Such experiments are relatively inexpensive and the results can often be used as a guide in planning more extensive and expensive field experiments.

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DISCUSSION OF

"A METHOD FOR APPROXIMATING THE WATER CONTENT OF SOILS"

by NEDAVIA BETHLAHMY

[Trans., v. 33, pp. 699-706, 1952]

C. H. M. van Bavel and M. J. Gilbert (Agronomy Department, North Carolina State College, Raleigh, N. C.)--Part of the paper, concerned with calibration, installation, and use of the Colman fiberglas units, gives the impression that in following the described procedure the obtained values for moisture content are sufficiently accurate for the purposes of hydrological studies.

The question remains whether the value for moisture percentage indicated by an element at given depth is a dependable estimate of the moisture content there, as averaged over the horizontal area that one wishes to characterize. How well can one replicate measurements with Colman units at the same depth and site? Our experiences with similar installations have been rather disappointing with respect to the variation between replicate installations. Probably, this is to be explained by the small "action radius" of Colman units and by the incidence of lag. This objection seems to apply equally to all types of resistance units that have been or are being used in the measurement of soil moisture.

We question whether shifting of laboratory calibration curves to agree with field checks is justifiable. One does not expect the deviation of the field calibration from the laboratory calibration to be constant within the range covered. In the article by HENDRIX and COLMAN [1951] it appears that, where deviations between field and laboratory curves resulted, these were not constant over the range of measurement. Our experience on this point indicates a behavior similar to that found by Hendrix and Colman.

On the basis of the foregoing and on the basis of much work with Colman units in field and laboratory, we feel that it is unsafe to conclude that single stacks of these elements will give the moisture content of soils with the accuracy that is needed in hydrologic studies. This is not to be taken as a criticism of the Colman elements themselves. It is well known that wide variation in soil characteristics related to soil moisture exists from point to point in field soils. With triplicate installations at each depth as first suggested by Colman (Manual of instructions for use of the fiberglas soil-moisture instrument, Berkeley Scientific Co., 1947), and a sufficient number of such installations, a fairly adequate picture of soil moisture can be obtained for a given area.

In regard to the calculation of the amount of water held per unit of surface in a soil stratum under study, the author proposes to adjust the bulk specific gravity (W) according to the soil-moisture content (M). The soil layer covered by the measurement of a single element has a certain thickness, here to be called T. The value of W is taken to vary with M according to Eq. (14) and the amount of water held by the layer under study calculated as

$$Y = WTM/100 \qquad \text{(equivalent to Eq. (8))}$$

assuming for simplicity of argument the rock content to be zero. The author appears to assume that T is constant. But it seems that T varies with varying moisture content just as W, but oppositely so, because of

$$W = \text{mass of oven-dry soil}/T$$

per unit horizontal surface. The mass of the oven-dry soil per unit horizontal surface in a defined stratum does, of course, not change, even though the dimension and bulk density change.

If one takes the expansion and contraction of the soil layers into account, it is seen then that these cancel the effect of changes in density, regardless of the nature of the function giving the latter as determined by moisture content. If one determines the thickness (T) of the layer contained between the two points midway between elements and, concurrently, determines the moisture content by weight (M) and the bulk density (W), the moisture content in inches of water is given under any condition by

$$Y = WTM/100$$

if T is expressed in inches, W in g/cm^3, and M in per cent.

The views stated above lead us to conclude that the method of calculation proposed by the author is in error. This is true also when a measurable content of rock is found in which case the correct formula is

$$Y = WTM(100 - R)/100$$

In which R is rock content in per cent by volume.

As shown by the formulas given by us, there is no need to invoke the use of feet and pounds in the calculations. Although this is not in error, it only leads to confusion.

The finding of the author "that a parobolic curve results when inches of water are plotted over moisture percentage" could have been predicted. For, his (9) is a second-degree function in M and, with the proper relation of the coefficients kA and kc, should give a curve that, within the range of M found, first ascends almost linearly and then descends again after going through a maximum. But it seems incorrect to state that this maximum should occur at the saturation percentage.

Let it be finally pointed out that a water balance sheet as given in Table 8 by the author can only be taken as proof for the adequacy of the measurement of one component, if all others are evaluated with accepted methods of known accuracy. The other components may include, in addition to those listed by the author, surface runoff, foreign water, subsurface runoff and-influx, and soil-moisture movement, both upward and downward.

Reference

HENDRIX, T. M., and E. A. COLMAN, Calibration of fiberglas soil-moisture units, Soil Sci., v. 71, pp. 419-427, 1951.

Nedavia Bethlahmy (Northeastern Forest Experiment Station, Upper Darby, Pa., Author's closure)--Hydrologic research is conducted by means of sampling. We sample precipitation, ground water, soil moisture, and other variables. Soil-moisture units are used simply to sample soil-moisture content, and their use should be consistent with good sampling methods.

Because soils are a continuous variable, they must be sampled at different places. In field installations of soil-moisture units, one may place several units in the same pit within a given horizon or depth; or, as an alternative, set up two separate installations in close proximity. Table 9 presents data for soil-moisture installations that are within 20 ft of each other.

In Table 10 are listed some results (by the direct sampling method) of sampling the same horizon at contiguous spots. The total difference listed in Table 10 accounts for a much greater difference than shown in Table 9. In other words, in a given soil, moisture differences within a few inches may be as great as within a few feet.

However, in hydrologic research we are more interested in the daily consumptive figure than in the absolute soil-moisture content. Column six in Table 9 shows the difference in consumptive use at two neighboring sites. Over a ten-day period, the total difference amounts to 0.38 inch. It is highly doubtful that a single installation with duplicate or triplicate units in a given horizon would indicate such a large variation in consumptive use, because the latter is a function of root distribution.

Needless to say, a single installation with only one unit per horizon is not good sampling. But from a quantitative point of view, consider the following case. From Table 9 we obtain two estimates of consumptive use: 0.65 inch and 1.03 inches for a ten-day period. Assume that the same rate would continue for a whole month. Then the two estimates of consumptive use for the entire month are 1.95 and 3.09 inches with an average of 2.52 inches. If only a single installation were in use, then the error would have been ± 0.57 inch. In humid climates this figure is not too gross for hydrologic work. On the other hand, in arid climates the estimates would probably not differ that much.

Table 9--Comparison of total water content (to 27-inch depth) and daily differences at adjacent sites

Date	Soil-moisture content				Col. 5 - Col. 3
	Site 1		Site 2		
(1)	Amount (2)	Difference (3)	Amount (4)	Difference (5)	(6)
1952	inch	inch	inch	inch	inch
July 21	5.38		4.50		
		0.00		0.05	0.05
22	5.38		4.55		
		0.10		0.10	0.00
23	5.28		4.45		
		0.08		0.09	0.01
24	5.20		4.36		
		0.12		0.19	0.07
25	5.08		4.17		
		0.08		0.16	0.08
28	5.00		4.01		
		0.04		0.04	0.00
29	4.96		3.97		
		0.11		0.19	0.08
30	4.85		3.78		
		0.12		0.21	0.09
31	4.73		3.57		
Total		0.65		1.03	0.38

Table 10--Variation in soil-moisture content at contiguous spots (to nine-inch depth); (direct sampling method)

Horizon	Sample	Moisture content	Moisture-content difference	
		pct of dry wt	pct	inch
Humus	1	274.0		
			83.9	0.39
	2	190.1		
A_2	1	28.0		
			9.3	0.16
	2	18.7		
B_2	1	37.6		
			13.7	0.35
	2	23.9		
B_{31}	1	20.8		
			3.5	0.27
	2	17.3		
			Total	1.17

The author's work was done in the humid Northeast where the soils do not dry out as much as those in arid climates. Hence, the range of the field "check" points is not very great. In a few cases, the data showed a tendency toward smaller deviations at the high resistances. Hendrix and Colman found no discrepancy when undisturbed soils were used. The author's laboratory calibrations were also conducted on undisturbed soils.

If the laboratory curves are to be translated laterally in accordance with field checks, then the question of differential displacement becomes significant when related to hydrologic studies, particularly in arid climates where the soil is reduced to its wilting point several times during a year. Hendrix and Colman give a maximum deviation of 4.5 pct at field capacity and 1.0 pct at wilting point, a difference of 3.5 pct. Assuming four drying periods per year and a volume weight of 1.30, then consumptive use in a foot of soil would be overestimated by about 2.18 inches of water. Of course, in humid climates the error would amount to only a fraction of this figure. On the other hand, if no differential displacement occurs, then calibration curves can be translated laterally without introducting any errors.

The third question which van Bavel and Gilbert raise is a very interesting one. The use of soil-moisture units in hydrologic research is based on the assumption that a unit installed at a given depth remains permanently at that depth. Obviously, if a given unit is continuously changing its location, then it is quite beyond our means to evaluate hydrogically the information it yields. The assumption of constant depth is predicated on a working hypothesis that the rocks and stones within a soil are the framework of the soil; and that all mineral soil expansion occurs against this firm background. In other words, all the stresses induced by the expansion of the soil are taken up at a multitude of points throughout the soil mass, wherever a rock is located. Thus, in general, a soil may be expanding, but the thin layers of soil adjacent to a rock are contracting. This working hypothesis may be partially confirmed by observing the structure of a soil after a storm. In general, the soil may be well aggregated, but the soil next to a rock is dense and compact.

It is this hypothesis which leads to difficulties in calculating the soil-water content. At the higher moisture contents (above field capacity) part of the soil has a low bulk density, while a smaller part has a high density; but our information is only about the former. Hence the need for adjusting the bulk density figures. These figures were adjusted to agree with another experimental finding: the laboratory calibration curves.

Finally, note that, in practice, the use of a constant volume weight and thickness (as proposed by van Bavel and Gilbert) does not yield good results. The method was discarded in favor of the present one because following a rain it resulted in calculated water contents larger than the actual precipitation recorded in a rain gage.

DISCUSSION OF

"THE EFFECT OF SURFACE HEAD ON INFILTRATION RATES BASED ON THE PERFORMANCE OF RING INFILTROMETERS AND PONDS"

by LEONARD SCHIFF

[Trans., v. 34, pp. 257-266, 1953]

Robert W. Stallman (U. S. Geological Survey, Washington 25, D. C.)--The readily available published literature on the use of infiltrometer data indicates that a semiqualitative approach is being used generally for both data collection and application of the analytical results to prototype structures. Although Schiff's paper serves admirably well for emphasizing the effect of surface head on infiltration rates, it seems possible to extend his approach to a more quantitative analysis. With the proper equation for analysis of infiltrometer data, it should be possible to determine directly the vertical permeability of the soil column, and the "coefficient of saturation." Then the effects of surface head for prototype infiltration installations can be predicted and the variation of infiltration rate with time can be computed from the known hydraulic characteristics of the soil.

The head loss between the soil surface and the wetting front in the soil equals the sum of the surface head, the thickness of the saturated zone, and the capillary head difference across the wetting front. In comparatively dry fine-grained isotropic soils the capillary head difference across the wetting front may be the principal force causing infiltration, particularly if the depth of penetration of the wetting front is small compared with the capillary head difference. Let $h = h_w + h_s$, where h_w is the constant head at the soil surface, and h_s is the thickness of the saturated zone between the soil surface and wetting front, at any time, t, since infiltration began. It follows, from application of Darcy's law, that

$$Q = P\,(h - h_c)/(h - h_w) \qquad (1)$$

where Q is the instantaneous rate of discharge through a unit area of soil surface, P is the soil permeability, and h_c is the difference in capillary head (assumed to be constant) across the wetting front. The total volume of water discharged through the soil per unit area, at any time, t, since the infiltration began, can be expressed as

$$V_t = S_c\,(h - h_w) \quad \ldots\ldots (2)$$

where S_c is a coefficient of saturation defined as the volume of water per unit gross volume of the soil required to fill the voids to the degree of saturation normally attained behind the advancing wetting front. This degree of saturation is usually found to be about 75 to 80 pct of porosity, and the corresponding permeability is about one-third that for complete saturation [WALLACE, 1948; BAVER, 1948]. A differential form of (2) is

$$dV_t/dt = Q = S_c\,dh/dt \quad \ldots\ldots (3)$$

Substituting for Q in (1) in terms of h gives

$$[(h - h_w)/(h - h_c)]\,dh = (P/S_c)\,dt \quad \ldots\ldots (4)$$

Integrating (4) between the limits h_w to h, and $t = 0$ to t yields

$$h - h_w + (h_c - h_w)\log_e[(h - h_c)/(h_w - h_c)] = (P/S_c)\,t \quad \ldots\ldots (5)$$

Values of P and S_c can be substituted in (5) from (1) and (2) to obtain

$$h - h_w + (h_c - h_w)\log_e[(h - h_c)/h_w - h_c)] = (Q/V_t)\,[(h - h_w)^2/(h - h_c)]\,t \quad \ldots\ldots (6)$$

Eq. (6) can be solved for h_c if the depth of penetration of the wetting front, at some time t, is observed. This can be done by observing changes in resistance at small specially designed resistance probes (similar in principle to the soil-moisture blocks) placed at known depths below the soil surface. As the wetted front passes the resistance probe, the increased moisture available in the vicinity of the probe will cause a rather sharp decrease in measured resistance. Knowing the depth of the probe, the time at which the wetted front passes through its position, and the values of h_w, Q, and V_t for the time thus determined, (6) can be solved for h_c. Eq. (1) and (2) can then be solved for P and S_c using these data. Once the hydraulic constants are evaluated, (5) can be used to compute the variation between h and t, and (1) can be used to predict the infiltration rate as a function of h or t.

The infiltrometer tests are necessarily of long duration if made to include the effects of the deeper soil layers. For fine-grained soils it is probable that moisture content affects the rate of infiltration observed. Therefore, tests of long duration may produce erratic results, depending on soil-moisture variations as a function of time. It seems desirable to observe soil-moisture content during the infiltrometer runs so as to further qualify the applicability of the test results. The time required to account for the hydraulics of the deeper soil layers can be reduced by using a small-diameter recharge well driven to the desired depth. As an example, consider the case of a fine-grained soil, partly saturated, in which the effects of gravity can be assumed negligible as compared with capillary forces in producing radial flow in all directions from a short, small-diameter well screen. The shape of the zone of saturation produced by recharging the well in an isotropic homogeneous soil is assumed to be a sphere. The discharge from the well (which is supplied with water at a variable rate and constant head) at any time t after recharge is begun is therefore given approximately as

$$Q = -\,4\pi r^2 P\,dh/dr \quad \ldots\ldots (7)$$

where h is the head in the saturated zone at the radius r, measured from the center of the well-screen axis. Integrating (7) between r_o and r_s, where r_s is the radius of the saturated sphere, we obtain

$$Q\,(r_s^{-3} - r_o^{-3}) = 12\pi P\,(h_c - h_o) \quad \ldots\ldots (8)$$

in which h_o is the head at the well screen and h_c is the capillary-head difference across the wetting front. At any time t, the total volume of water recharged is

$$V_t = (4/3)\pi S_c\,(r_s^3 - r_o^3) \quad \ldots\ldots (9)$$

from which

$$r_s^3 = 3V_t/4\pi S_c + r_o^3 \quad \ldots\ldots (9a)$$

Substituting this value of r_s^3 in (8) there follows

$$Q\,[1/(3V_t/4\pi S_c + r_o^3) - 1/r_o^3] = 12\pi P\,(h_c - h_o) \ldots\ldots\ldots\ldots\ldots (10)$$

which indicates that Q becomes apparently constant at rather small values of r_s. If we observe the values of V_t at two values of r_s by resistance probes, a set of two simultaneous equations like (9) can be solved for S_c and r_o. The resistance probes should be located at small radii from the recharge-well screen for maximum accuracy in determining r_o and S_c. Eq. (8) can then be solved for h_c and P through use of the infiltration rates, Q, as observed.

Eq. (1) through (11) apply only to isotropic and homogeneous soils. Therefore they are not suited for application to the usual field problem. However, other analytical expressions can be derived to accomplish the same end: of determining P and S_c from infiltrometer data, or similar testing techniques. Once the hydraulic constants are evaluated for given soil-moisture conditions or surface treatments, it should be convenient to compute the hydraulic activity of prototype recharge works directly, considering the boundary geometry in detail.

Leonard Schiff (Soil Conservation Service, P. O. Box 513, Bakersfield, Calif., Author's closure)--Developments toward quantitative analyses of infiltrometer data are an ultimate goal and Stallman's suggestions should be helpful. Wide use is made of infiltrometers with some confusion as to field procedures as well as analysis. The type of data obtained and their analyses are dependent upon soil properties, including the soil-moisture content, forces motivating flow, and the depth of the infiltrometer. For example, under prolonged submergence as in water spreading, capillary forces are negligible and movement of water is largely vertically downward. For an infiltrometer to yield data representative of field conditions under prolonged submergence, it appears desirable to drive the infiltrometer to a depth where hydraulic head is small. At such a depth little lateral flow will occur at the bottom of the infiltrometer. If such depths are impractical, a balanced buffer or pool of water of equal depth surrounding the infiltrometer is helpful. If water builds up on a less pervious horizon below the infiltrometer, lateral flow will occur over this horizon. This lateral flow is partially supplied by the water moving through the infiltrometer and the value of a buffer is reduced. If capillary forces predominate, as they do in furrow irrigation when the surrounding soil is relatively dry, a shallow unbuffered infiltrometer appears to be best. When it is necessary to eliminate the influence of capillary forces adjacent to an infiltrometer, as in the paper under discussion, it is desirable to conduct tests after some wetting or with the aid of a buffer.

In the experiments the degree of saturation was sufficient to permit application of the continuity equation as well as the Darcy equation. Capillary forces were negligble. Stallman's equations permit consideration of the capillary forces; however, they apply only to isotropic and homogeneous soils, and, as he points out, are not suitable for field application. The hydraulic constants would have to be evaluated for application to soils of various properties, moisture conditions, and treatments. Perhaps it would be best to develop an analytical expression for the saturated front, which frequently exists in the soil within the infiltrometer, and another analytical expression for the movements below and around the infiltrometer with a boundary condition of capillary forces while they exist.

If soil-moisture blocks are used to determine the movement of water and the degree of saturation, relationships may be established between soil pores, transmission rates or velocities, soil-moisture content, and soil properties [SCHIFF and DREIBELBIS, 1949ab]. Results may be related to the heads involved as discussed. This approach may be the simplest for field evaluation.

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REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

O. G. SUTTON, Micrometeorology, a study of physical processes in the lowest layers of the Earth's atmosphere, McGraw-Hill, xii + 333 pp., 1953, $8.50.

Sutton's Micrometeorology is an important and welcome contribution. It fills a definite gap in its field, and is written by an authority who has devoted much of his career to the subject. The book has eight pages of author and subject index. Each of the eight chapters is well documented, mostly from British publications. Pertinent theories and methods of attacking the problem are presented in a progressive manner, both historically and logically. Each chapter is carefully organized and is introduced by a helpful discussion in simple language of what is to follow in more precise and mathematical terms. It would be helpful if each chapter also had a summary of conclusions. The few typographical errors noted by this reviewer are too obvious to be misleading. Some readers may experience frustration when they refer to the book for specific information on limited aspects of the subject and find that definitions of symbols and terms are scattered throughout the book and that much of the treatment relies heavily on what has preceded.

The first chapter, "The atmosphere at rest," is a brief and factual review of pertinent physical constants of the static or average atmosphere.

The next two chapters deal with laminar and turbulent flow, respectively. Here and in other places considerable emphasis is given to the geostrophic wind, with possibly too little reference to the gradient wind. The second chapter includes a development of the traditional and classical equations of motion. Pockels' treatment of air flow over undulating terrain is presented in some detail, but so many stated and implicit simplifying assumptions must be made in the abstract and theoretical treatment of such problems that little is left beside the mathematical exercise.

Early in Chapter 3 is a discussion of a definition of turbulence and of the difficulty inherent in studying a phenomenon that is yet to be defined in mathematical terms or in words. The author discusses in general terms the fact that an air thermometer measures not merely what is theoretically regarded as air temperature, but usually indicates the integrated effect of many elements such as solar radiation, wind speed, and even wind direction. Further, this integration is not only among a variety of elements and conditions but is also over considerable time and space. Of course, it is the author's prerogative to determine the scope of his own book, but it seems regrettable that he did not discuss this important subject in quantitative terms, or even refer to Middleton's work. In section 3.6 he devotes nearly three pages to a detailed derivation based on an assumption which he finally states is regarded as untenable. Good attention is given to the spectrum of turbulence, a subject that is developing rapidly.

The fourth chapter, "Heat transfer and problems of diffusion," applies the classical theory of heat conduction to atmospheric problems. The subject develops by successively introducing problems inherent in a laminar layer, free convection and forced convection.

To make the treatment comprehensive, radiation is the subject of Chapter 5. This subject is not treated with the mastery that can come only from the experience the author has had with other aspects of micrometeorology. He neglects the convenience of the term "langley." His dependence on the work of others is evidenced by his use of oft-quoted and questionable values of the Earth's radiational balance, ignoring the work of Fritz published in the Journal of Meteorology in 1949. In Table 7 are values of albedo of grass-covered ground which are higher, and of snow which are lower, than those generally accepted on the basis of more recent work than that quoted, 1936. The albedo of new snow, for example, approaches 0.90. Values less than 0.40 generally involve a combination of snow and ground, or excessive deposits of debris on the snow surface.

The subject of Chapter 6 is "The temperature field in the lowest layers of the atmosphere." Some of the few places in the book where observational data are given are found in this and the following chapter. The chapter includes some refreshing discussion of the practical problems of sampling, and even of defining the soil surface. Chapter 7 discusses "Problems of wind structure near the surface."

The concluding chapter discusses diffusion and evaporation. Unfortunately this chapter suffers from the coincidence that it was published shortly after, but was started too soon to incorporate the results of, the report on the Lake Hefner Project, USGS Circ. 229. The Lake Hefner Report confirms one of the author's evaporation formulas, his conclusion that most natural surfaces are aerodynamically rough, and a tentative conclusion that stability ordinarily has little effect on evaporation. While he raised the question as to the value of observations of pan evaporation, he also predicted a useful correlation between pan evaporation and that from reservoirs. This prediction has been confirmed in the Lake Hefner work. The effect of length of downwind path is still unsettled, though it seems that concern about this aspect has as little justification as concern about stability.

This reviewer enjoyed the author's discussion of the relationships between theory and observation and of the disciplines of controlled experiment versus those of the literally free atmosphere. As with any difficult and growing subject of inquiry there are many controversial aspects, but the author has courageously given his opinions in many instances where observations or theory are still deficient. While it is the duty of a reviewer to be critical, this reviewer found little to criticize beyond what he has cited above. Great praise is due the book which should find a useful place on thousands of desks. While the book is preponderantly theoretical and mathematical, the author takes evident pleasure in quoting Brunt to whom the book is dedicated, in saying "The air does not know its own temperature with 'that' degree of accuracy."

WALTER T. WILSON

BIBLIOGRAPHY

Scope of this Bibliography

This statement replaces the one published in the February, 1952, issue of the Transactions, pages 129-130, and the modifying amendment pertaining to Meteorology published in June, 1953, page 492. In general, it involves only slight changes. This will serve as the guide to the selection of material for the current volume. The bibliography does not include papers appearing in the Transactions or in the usually available journals devoted in large part to any aspect of geophysics, except as the following statements may indicate. Emphasis in general is placed on the fundamental aspects of the several fields rather than their applications, and on out-of-the-way sources likely to escape general notice. Except in Oceanography, only occasional Russian items are covered.

General--The items include those of broad interest in geophysics, and those of specific interest to two or more Sections, garnered in the search of the literature of particular Sections, especially from foreign and out-of-the-way domestic publications.

Geodesy--Papers on theoretical geodesy and on significant geodetic operations and results are included. However, articles appearing in the Bulletin Géodésique and in the Empire Survey Review are excluded, these journals being regarded as primary sources for the field. Excluded also, as a general rule, are papers on photogrammetry and cartography.

Terrestrial Magnetism and Electricity--This heading covers geomagnetism, telluric and atmospheric electricity, air glow, aurora, and studies of the ionosphere as a geophysical entity, with limited attention to collateral fields such as radio astronomy and cosmic rays. Some items which concern one of these topics, but which appear in journals not devoted chiefly to that topic, are included. Thus, a paper on cosmic-ray variations appearing in Proceedings of the Institute of Radio Engineers, or one on ionospheric radio propagation in Physical Review, might be included, whereas neither would be entered if their sources were reversed. Papers in the Journal of Geophysical Research and the Journal of Atmospheric and Terrestrial Physics are excluded. Items (from any source) that have been listed in W. E. Scott's list of Recent Publications in the Journal of Geophysical Research are not intentionally repeated here.

Meteorology--Emphasis is placed on items gleaned from the less well-known foreign publications and from publications generally of a non-meteorologic nature. Meteorological Abstracts, published monthly, largely supplies the needs in this field. Specifically excluded are: Monthly Weather Review; Journal of Meteorology; Bulletin, American Meteorological Society; Weatherwise; Quarterly Journal, Royal Meteorological Society; Weather; Indian Journal of Meteorology and Geophysics; Papers in Meteorology and Geophysics of the Meteorological Research Institute of Tokyo;

Journal, Meteorological Society of Japan; Geophysical Magazine of the Central Meteorological Observatory, Tokyo; Tellus; Journal Scientifique de la Météorologie; Météorologie; Zeitschrift für Meteorologie; Annalen der Meteorologie; Meteorologische Rundschau; Archiv für Meteorologie, Geophysik, und Bioklimatologie, Series A; and Boletin, Servicio Meteorologico Nacional (Spain).

Oceanography--All aspects of Oceanography are covered save the purely biological. Readily available journals devoted in substantial measure to Oceanography are excluded, notably Journal of Marine Research, Papers in Physical Oceanography and Meteorology, Bulletin of the Beach Erosion Board, Journal du Conseil Permanent International pour l'Exploration de la Mer, Deutsche Hydrographische Zeitschrift, Bulletin d'Information du Comité Central d'Océanographie et d'Étude des Côtes, International Hydrographic Review, Oceanographical Magazine (Tokyo), and Deep Sea Research.

Hydrology--Includes much of the current literature developing hydrologic principles. It is selective only to the extent that regular serial reports on stream flow, ground water, climatology, and other basic data are excluded. Also excluded are engineering reports based on hydrologic applications, unless it is found that some new principle is set forth. It is not complete, especially in some of the peripheral aspects, such as glaciology and sedimentation.

Seismology--All aspects are covered except applications to prospecting, but the more common sources are omitted. Papers that are primarily geological, or that are more properly assigned to Tectonophysics, are omitted.

Volcanology--All aspects of the broad field of Volcanology are included, including petrology, heat processes, radioactivity, and geochemistry as they relate to geophysics, as well as classical Volcanology, except items from publications usually available in the libraries of schools where the Earth sciences are taught (such as the Bulletin of the Geological Society of America, American Mineralogist, American Journal of Science, and the Journal of Geology). Out-of-the-way publications and journals, and other foreign publications, are emphasized.

Tectonophysics--All aspects of Tectonophysics are included, but the journals readily available in the United States are not covered (see under Volcanology). It is the intent to include general geologic papers having detailed discussion of structure.

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NOTES AND PERSONALIA

NOTES

Corrigendum--In the issue of August, 1953, in the paper by Chi-san Shu on Trilateration, page 514 in the line immediately following Eq. (12), M should be m.

Congress on Alpine Meteorology--The Third International Congress on Alpine Meteorology will be held at Davos-Platz, Switzerland, April 12-14, 1954. The agenda includes the following general titles as they relate to alpine meteorology: Synoptic meteorology, Radiation, Bioclimatology, and Snow and ice. Plans include visits to various Swiss institutions and installations following the meeting. Interested persons should get into touch with Dr. W. Mörikofer, Observatoire physico-météorologique, Davos, Switzerland.

Research Fellowships and Assistantships in Meteorology and Oceanography at New York University--Two fellowships and several assistantships in meteorology and oceanography have been announced by the Graduate Division, College of Engineering, New York University, New York 53, N. Y. Completed forms and supporting material relating to the fellowships should be filed by April 1, 1954.

Summary of major accomplishments in geophysics in 1953--Science Service has prepared a summary of progress in various aspects of science and technology, including one on geophysics and other aspects of the Earth sciences. A copy of the review or information on any specific item may be received by writing to Science Service, 1719 N Street, N. W., Washington 6, D. C., sending two three-cent stamps.

Positions for oceanographers--The Civil Service Commission has announced an unassembled examination for oceanographers (GS-5 through GS-15) for duty in the Navy Hydrographic Office and other Federal establishments. Interested persons should get into touch with the Civil Service Commission in Washington or one of its field offices.

Conference on radio astronomy--A conference on radio astronomy, sponsored jointly by the National Science Foundation, the Carnegie Institution of Washington, and California Institute of Technology, was held at the Carnegie Institution of Washington, January 4-6, 1954, with about 100 in attendance.

New publication in oceanography--A new quarterly publication, Deep-Sea Research, issued by Pergamon Press in London, has begun with the issuance in October, 1953, of volume 1, number 1. This is the outgrowth of the concept of Hans Pettersson in 1946, and has been brought into being through the Joint Commission on Oceanography of the International Council of Scientific Unions. The first issue contains seven papers bearing on various aspects of the subject matter indicated by the title listed in the Bibliography on Oceanography in the next issue. Inquiries should be sent to Pergamon Press, Ltd., 242 Marylebone Road, London, N. W. 1, England. The price is $12.60 per year.

Guest lecturers at the Institute of Geodesy, Photogrammetry, and Cartography of Ohio State University--During the fall months of 1953, guest lecturers at the Institute included F. A. Vening Meinesz, Professor of Geodesy and Geophysics at Utrecht University, The Netherlands, who gave a series of lectures on Geodetic applications of gravity anomalies; R. Roelofs, Director of the Institute of Geodesy and Photogrammetry of the Institute of Technology of Delft, The Netherlands, who gave a series of lectures on Theory of errors and its application to photogrammetry; T. J. Kukkamäki of the Finnish Geodetic Institute, who gave two series of lectures on Geodetic adjustment computations, and map projection. In the winter and spring terms, Bertil Hallert, Director of the Institute of Photogrammetry of the Institute of Technology, Stockholm, will give lectures on various aspects of photogrammetry. In addition to these special lectures, regular courses which began in the fall of 1952, are continuing.

Symposium on Geophysics and Geophysical Geodesy--A Symposium on Geophysics and Geophysical Geodesy was held at the Institute of Geodesy, Photogrammetry, and Cartography of Ohio State University on November 12-13, 1953. Fourteen papers from authorities in the United States, Canada, The Netherlands, Finland, and Japan were presented on various aspects of the field.

Development of teaching and research in geophysics at the University of Wisconsin--A recent report issued by the University of Wisconsin indicates increasing student interest and research work in geophysics. The latter includes a world network of gravity bases with over 2000 primary bases in 70 countries sponsored by the Office of Naval Research; the establishment of a series of high-precision gravity values to facilitate calibration of high-range gravimeters sponsored by the Air Force Cambridge Research Center; establishment of a regional reconnaissance network of gravity and magnetic observations at 10- to 15-mile intervals over the United States sponsored by the Air Force Cambridge Research Center; seismic refraction mapping of the basement rock surface beneath the coastal plain of the Southeastern States sponsored by the Office of Naval Research; extensive gravity, magnetic, and seismic surveys in Wisconsin and other mid-western areas; and work on instrument development and analytical studies. Graduate students in geophysics have increased from two in 1949 to 13 currently.

Arctic Bibliography--The Arctic Institute of North America, with the sponsorship and support of the Army, Navy, and Air Force, is completing an extensive Arctic Bibliography in five volumes through 1953. The first two volumes, through 1949, contain 20,000 annotated listings arranged alphabetically by authors. The third volume contains a subject index. The three volumes contain 4500 pages, and are available through the Superintendent of Documents, Washington 25, D. C., for a price of $12.75. The Directing Committee has worked under the direction of Henry B. Collins of the Smithsonian Institution, with Marie Tremaine as Editor.

Bibliography on snow, ice, and permafrost--The Library of Congress is preparing a continuing bibliography with abstracts under an agreement with the Snow, Ice, and Permafrost Research Establishment. Abstracts on the basic properties and applications of snow, ice, and perennially and seasonally frozen ground are printed on conventional three-by-five-inch cards. Each item is completely cataloged and the location of the original publication is included. Any number of cards may be ordered at a price of three cents each. Orders and inquiries should be directed to the SIPRE Bibliographic Project, Library of Congress, Washington 25, D. C.

PERSONALIA

Maurice L. Albertson, Professor of Civil Engineering and Head of Fluid Mechanics Research at Colorado A and M College, is on a Fulbright Fellowship on research work at Grenoble, France.

Sydney Chapman, President of the International Union of Geodesy and Geophysics and Professor of Geophysics at Cambridge University, retired, has an appointment as Professor of Geophysics at the Geophysical Institute, University of Alaska, until March 1, 1954, following which, until May 15, 1954, he will take up duties in the Department of Physics of New York University.

George D. Clyde, formerly with the Soil Conservation Service at Logan, Utah, has taken up duties as Director of the Water and Power Board and Commissioner of Interstate Streams for the State of Utah.

E. A. Eckhardt, Vice President of Gulf Research and Development Co. and Associate Director of Research, has recently retired.

Paul D. Foote, Vice President of Gulf Oil and Refining Co. and Executive Vice President and Director of Gulf Research and Development Co., has recently retired.

W. A. Heiskanen, Director of the Institute of Geodesy, Photogrammetry, and Cartography of Ohio State University, and Director of the Finnish Geodetic Institute, has been given the Wihuri Foundation Award, considered as one of the highest Finnish awards, for his outstanding international work relating to geodesy and geophysics and for his efforts on behalf on Finland's cultural advancement.

E. Wendell Hewson, formerly of Massachusetts Institute of Technology, is now at the University of Michigan as Research Physicist in the Engineering Research Institute and as Lecturer in Meteorology in the Department of Civil Engineering.

Raymond A. Hill of Leeds, Hill, and Jewett, Consulting Engineers, has been named Chairman of a Board of Consultants on a study of the feasibility of a salt-water barrier in San Francisco Bay. Malcolm Pirnie of Malcolm Pirnie, Engineers, and Philip C. Rutledge of Moran, Proctor, Mueser, and Rutledge, Consulting Engineers, have also been named to the Board.

Embert A. LeLacheur, Oceanographer with the U. S. Coast and Geodetic Survey, retired at the end of 1953 after more than 35 years of service with the survey.

Donald H. Menzel has been named Director of the Harvard University Astronomical Observatory, succeeding Harlow Shapley.

Maynard Malcolm Miller, now on a Fulbright Fellowship on study at Cambridge University in England, specialist in glaciology, has been named by the United States Junior Chamber of Commerce as one of the Ten Outstanding Young Men of the United States in 1953.

William W. Reedy has returned to his work as Hydraulic Engineer in the Hydrology Branch of the Bureau of Reclamation, following a four-month leave period during which he was associated with Leeds, Hill, and Jewett, Consulting Engineers in Los Angeles.

S. Fred Singer, until recently in the London Branch Office of the Office of Naval Research, is now Associate Professor of Physics at the University of Maryland, College Park, and is setting up a research program for work on cosmic rays.

David Keith Todd has recently taken his Ph. D. degree in Civil Engineering at the University of California in Berkeley and has been appointed Assistant Professor of Civil Engineering there.

A. L. Washburn has taken up duties as Professor of Northern Geology at Dartmouth College.

Gordon R. Williams, until recently an engineer with Knappen-Tippetts-Abbett-McCarthy, Consulting Engineers, has taken up duties as Associate Professor of Civil and Sanitary Engineering at Massachusetts Institute of Technology.

UNION, SECTION, AND COMMITTEE ACTIVITIES

REPORT OF THE DELEGATES OF THE AMERICAN GEOPHYSICAL UNION TO THE FOURTH NATIONAL CONFERENCE FOR UNESCO IN MINNEAPOLIS, SEPTEMBER 15-17, 1953

Athelstan F. Spilhaus and Donald B. Lawrence

The meetings were attended by about 800 representatives and delegates of U. S. national organizations who were called together by the U. S. Department of State in accordance with Public Law 565, 79th U. S. Congress, Second Session, to consider "America's Stake in International Cooperation." The conference began with an evening open to the public, featuring formal greetings, and addresses by Walter H. C. Laves, Chairman, U. S. Commission for UNESCO, and by Walter Bedell Smith, Undersecretary of State. There followed the American premier of a new UNESCO film "World Without End," a stirring documentary film on the work of UNESCO in Mexico and Thailand to improve human understanding and alleviate human suffering.

The following morning was occupied by four sectional meetings, each conducted by a panel of invited speakers discussing various phases of the relation of UNESCO to world problems. In the afternoon each section subdivided into "work" groups of about 40 persons, but unfortunately most of these were actually organized in the form of symposia on special topics which in most instances provided almost no opportunity for audience participation. The Work Group (A-4) in which both of the AGU delegates participated was "The Mobilization of Science and Technology to Improve the Living Conditions of Mankind." Chairman was Jan O. M. Broek, and Panel Participants were Elvin C. Stakman, Harold Macy, Ralph L. Goetzenberger, Gaylord W. Anderson, and John T. Edsall. Near the close of the meeting a committee consisting of E. C. Stakman, Maurice B. Visscher, D. B. Lawrence, and J. T. Edsall was appointed by the Chairman to help formulate a set of findings of this Work Group. These findings were ably presented by Edsall at the Final General Session the next day. The following needs were stressed.

(1) Substantial increase in the budget of UNESCO, which was only about nine million dollars for 1953 for all 69 member nations, particularly an increase in the natural science budget, which was only about $800,000 in toto this year. (It was pointed out that the size of the U. S. contribution and hence of the total budget for UNESCO was strictly regulated by the U. S. Department of State.)

(2) Wider appreciation of the devastating effect which continued growth of human population in excess of the world food supply can have on any effort UNESCO can make in other ways toward improving the living conditions of mankind.

(3) Improved quality of teachers, particularly natural science teachers.

(4) Improved techniques of communication between peoples of different language, especially by indexing and abstracting the literature of natural science on an international scale.

(5) Reduced restrictions on free flow of scientists and literature from the United States to UNESCO member nations.

The general tenor of the meeting was friendly, great interest and hope for international cooperation were expressed, and realization of the importance of America's stake was recognized by the delegates and by the public in attendance at the Conference. Nevertheless, it seemed obvious to the delegates of AGU that significant progress on a global scale could not be expected without an increase in the annual budget of UNESCO.

The American Geophysical Union, as one of the national organizations in science, should support an increased emphasis on the value of the natural sciences in furthering UNESCO's objectives. The invidual members of AGU also might try to improve the situation by writing to their congressmen urging that the Department of State propose a liberal increase in the U. S. contribution to the UNESCO budget.

THIRTY-FIRST REGIONAL MEETING, BOSTON, MASS., DECEMBER 28-30, 1953

The Thirty-First Regional Meeting of the American Geophysical Union was held on December 28-30, 1953, in Boston, Massachusetts in conjunction with the 120th Meeting of the American Association for the Advancement of Science. On December 28 and 29, the AGU cosponsored three symposia: Physics of the Upper Atmosphere, The Sea Frontier, and Water for Industry.

The Union's session on December 30 consisted of a program of 14 papers. The morning session covered the fields of Terrestrial Magnetism and Electricity, Oceanography, Meteorology, Hydrology, Geodesy, and Seismology. The afternoon session was devoted primarily to Seismology. Speakers represented the Geophysics Research Directorate of the Air Force Cambridge Research Center, Woods Hole Oceanographic Institution, Lamont Geological Observatory of Columbia University, Wayne University, Harvard University, Massachusetts Institute of Technology, and Wallace E. Howell Associates. Edward H. Smith, Director of Woods Hole Oceanographic Institution, presided at the morning session, and James A. Peoples of the Air Force Cambridge Research Center presided at the afternoon session. National President James B. Macelwane and General Secretary John Putnam Marble were in attendance.

WALTER BAGINSKY, Secretary
Committee for the Regional Meeting

SPECIAL ANNOUNCEMENTS

Thirty-Fifth Annual Meeting, Washington, D. C., May 3-5, 1954--Attention is called to previous announcements in the Transactions, especially October, 1953, page 823, and December, 1953, page 974, concerning the Thirty-Fifth Annual Meeting of AGU to be held in Washington, D. C., May 3-5, 1954. Program details are being quite rapidly worked out, and some Sections already have their programs about complete. Those who desire to present papers should delay no longer. Three copies of the titles and abstracts of papers should be in not later than March 10, 1954 (as set forth in the October announcement) with word concerning amount of time desired (ten to 20 minutes usually allowed) and projection equipment needed. Filled programs will be closed in advance of March 10. Information (in triplicate) may be sent to the office of AGU or to the Section Secretary or Program Chairman as shown in the October announcement. The December announcement gives information regarding hotel reservations.

Tenth General Assembly of the International Union of Geodesy and Geophysics, and its Associations and Commissions--The Tenth General Assembly of the IUGG, its seven constituent Associations, and its Commissions will be held in Rome, Italy, September 14-29, 1954. All programs are now rapidly taking form, and although detailed programs are not yet available, these are set up in general terms. Those who are citizens of the United States and plan to attend should advise the office of AGU (the National Committee of the United States) as soon as possible, in order to be placed on the mailing list for special information as it becomes available, and in order that we may advise the Italian National Committee of accommodation needs. Travel reservations, especially if you are going by boat, should be made soon. As mentioned in the December, 1953, announcement (p. 974), it is possible to charter a special plane if sufficient numbers plan to go or return at one time. The per-capita rate for a full plane would be about $200 for the trip one way. Let the office know if you are interested in this possibility.

Student subscription rates--A subscription rate of $4.00 per calendar year has been set for bona fide full-time graduate and undergraduate students upon certification to that effect by the Head of the Department in which the student is majoring. This rate is not available to instructors or others who are essentially half- to full-time workers. The payment of $4.00 must accompany the certificate and order to eliminate the expense of correspondence and billing. The rate is offered strictly as a service to education, and to keep the cost of handling to a minimum all such subscriptions are entered only on the calendar-year basis. They are renewable only with a new certificate and may continue for a maximum of five years. A certificate form will be supplied upon request.

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TABLES FOR THE COMPUTATION OF THE TIDAL ACCELERATIONS OF THE SUN AND MOON

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Abstract--Tables are provided for facilitating the computation of the tidal acceleration of the Sun and Moon at a point on the surface of a rigid Earth. Without interpolation, the tables provide an accuracy of one microgal in the resultant computation. Higher accuracy is readily obtained by interpolation.

Introduction--The tide-producing accelerations of the Sun and Moon at a point on the Earth may conveniently be resolved into several portions. Firstly, into a part essentially constant in time, and into a portion fluctuating in the well-known tidal periods of approximately 12 and 24 hours. Only this fluctuating portion will be considered here. This fluctuating portion, in turn, is also conveniently divided into two parts: (1) the acceleration which would be experienced at the specified point if the Earth were perfectly rigid, and (2) a residual representing the total effects of the yielding of the Earth (including, of course, the deformation of the oceans) produced by the tide-generating attractions of the Sun and Moon. Of these two, only the former is considered here.

Methods of calculating the "rigid-Earth" tides have been published by DARWIN [1907], SCHUREMAN [1940], ELKINS [1943], and others. It is the purpose of this paper to supply tables for facilitating the computation of the vertical component of the tidal acceleration at any point on a rigid Earth, and to provide for a higher accuracy (one microgal) in the resultant computation than has previously been conveniently attainable. The residual portion due to the yielding of the Earth is of special geophysical significance, but it is small in magnitude, having a maximum double amplitude of less than 80 microgals. Since in practice this residual is obtained by correcting the observed accelerations for the theoretical rigid-body tidal effect, a precision of at least one microgal is desirable in the computation of the rigid-Earth tidal accelerations. The present tables provide such precision without interpolation. By interpolation, higher precisions may be attained if required.

Tide-producing acceleration of the Moon--On a rigid Earth rotating with constant angular velocity about its axis of symmetry, the only sources of fluctuations of gravity are variations in the position of the Moon and Sun. Let us consider the radial component of the tide-producing acceleration caused by the Newtonian force field of the Moon. (The difference between the radial and vertical components is neglected since it is considerably less than one microgal.)

The tide-producing acceleration at the point P (see Fig. 1) is the difference between the Moon's acceleration field at this point and the Moon's acceleration field at the center of the Earth. Hence, the radial (outward) component of the tide-producing acceleration is

$$g_m = -\gamma M_m \left[\cos z/\rho^2 - \cos(z+\epsilon)/\ell^2\right] \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

where γ is Newton's gravitational constant, ρ is the distance between the centers of the Moon and Earth, ℓ is the distance from the center of the Moon to the point P, ϵ is the angle between ℓ and ρ, z is the zenith angle of the Moon, and M_m is the mass of the Moon.

From Figure 1 we get the trigonometric relations

$$\left.\begin{aligned} \ell^2 &= r^2 + \rho^2 - 2\,r\,\rho\,\cos z \\ \cos\epsilon &= \sqrt{\ell^2 - r^2\sin^2 z}/\ell \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

Making use of (2) in (1) gives

$$g_m = -\left[\gamma M_m/\rho^2\right]\left[\cos z + (r/\rho - \cos z)/(1 + r^2/\rho^2 - 2\,r\cos z/\rho)^{3/2}\right] \quad \ldots\ldots \quad (3)$$

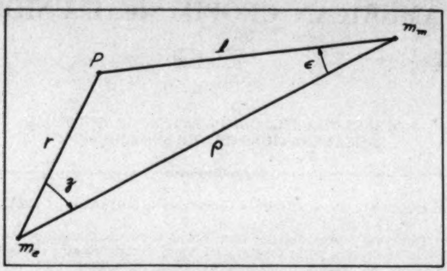

Fig. 1--Tidal acceleration of Moon

The well-known relationship between the declination δ, the local hour angle t, the zenith distance of the celestial body z, and the latitude ϕ of the observer is

$$\cos z = \sin \delta \sin \phi + \cos \delta \cos \phi \cos t \quad \text{(4)}$$

The distance r of the observing point from the Earth's center varies with latitude because of the departure of the level surface of the sea from a sphere; r also varies with the elevation of the point of observation above sea level. To take account of the latitude factor, the Hayford Spheroid will be adopted. In accordance with this convention,

$$r = C\, r_e + h \quad \text{(5)}$$

where r_e is the equatorial radius of the sea-level surface of the Earth, and h is the height of the observer above sea level. C is a function of latitude only, and is defined by the formula

$$\begin{aligned} C^2 &= [1 - (1 - r_p{}^2/r_e{}^2)(1 + r_p{}^2/r_e{}^2) \sin^2 \phi]/[1 - (1 - r_p{}^2/r_e{}^2) \sin^2 \phi] \\ &= [1 - 0.01340199 \sin^2 \phi]/[1 - 0.00672360 \sin^2 \phi] \quad \text{(6)} \end{aligned}$$

where r_p is the polar radius of the sea-level surface of the Earth.

The defining equation for the lunar horizontal parallax p is

$$r/\rho = C \sin p = \alpha \quad \text{(7)}$$

The radial component of the tide-producing acceleration of the Moon g_m can now be expressed as the product of three functions; the first is a constant for a given point P of the surface of the Earth, the second depends upon the horizontal parallax only, and the third is a function of the zenith distance and contains α as a parameter. These functions are defined by

$$\left.\begin{aligned} \lambda_m &= C^3 r_e{}^2/(C\, r_e + h)^2 = C\,[1 - 2h/Cr_e + 3h^2/C^2 r_e{}^2 - \ldots] \\ K_e &= -\gamma M_e/r_e{}^2 \qquad K_m = K_e\, M_m/M_e \\ f(\cos z, \alpha, K_m) &= K_m \left\{(\cos z)/\alpha + [1 - (\cos z)/\alpha]/(1 + \alpha^2 - 2\,\alpha \cos z)^{3/2}\right\} \end{aligned}\right\} \quad \text{(8)}$$

The final expression for g_m in terms of these three functions is

$$g_m = \lambda_m \sin^3 p\, f(\cos z, \alpha, K_m) \quad \text{(9)}$$

Tide-producing acceleration of the Sun--The tide-producing accelerations exerted by the Sun obviously may be described by a similar formula. However, the solar ephemeris lists the horizontal parallax for the Sun only to three places, but lists the values of the radius vector of the Earth to seven places. Therefore, it is better for our purposes to make use of D defined by

$$(\bar{r}_e/R) = D\,(r_e/R) \quad \text{(10)}$$

where $(\bar{r}_e/R)$ is the mean value of r_e/R, and R is the distance from the Earth to the Sun. Thus, we will define the three functions for the Sun to be

$$\left.\begin{aligned} \lambda_s &= C\,(1 + h/Cr_e) \\ K_s &= K_e\,(M_s/M_e)\,(\bar{r}_e/R)^3 \\ f\,(\cos z, \alpha, K_s) &= K_s\left\{(\cos z)/\alpha + [1 - (\cos z)/\alpha]/(1 + \alpha^2 - 2\,\alpha\cos z)^{3/2}\right\} \end{aligned}\right\} \quad \ldots\ldots (11)$$

The expression for g_s will then be written

$$g_s = \lambda_s\,D^{-3}\,f\,(\cos z, \alpha, K_s) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

We now define g_t to be the sum of the vertical components of the tide-producing accelerations of the Sun and Moon at the point P on the surface of a rigid Earth.

Tables of $f\,(\cos z, \alpha, K)$ were computed on the IBM computers of the National Bureau of Standards, Institute of Numerical Analysis on the UCLA campus. Table 1 gives these values of $f\,(\cos z, \alpha, K)$ vs $\cos z$, using α and K as parameters. This table holds for both the Sun and the Moon, and can be used to compute g_t to an accuracy of one microgal without interpolation. Values of $f\,(\cos z, \alpha, K)$ are listed to five decimal places to permit increased accuracy, if desired, by use of interpolation.

Table 2 lists values of sin p and $\sin^3 p$ for values of p at one-second intervals in the range 0°52′ to 0°60′.

Table 3 lists D^{-3} for values of D for the pertinent range of D, $0.9800 \leq D \leq 1.0209$, at intervals of 0.0001.

The following sample computation indicates the number of decimal places needed and the procedure in utilizing the tables to obtain g_t correct to one microgal.

Sample Computation

Station	U.C.L.A.		
Latitude (ϕ)	34°04′ N	$\sin\phi$	+0.5602
Longitude (λ)	118°10′ W	$\cos\phi$	+0.8284
Altitude (h)	432ft		

C	- from (6)	0.9994714
λ_m	- from (8)	0.9994714
λ_s	- from (11)	0.9994714

g_m (tidal effect of the Moon) = $\lambda_m f \sin^3 p$

g_s (tidal effect of the Sun) = $\lambda_s f D^{-3}$

Item	g_m	g_s
Date	July 1, 1952	July 1, 1952
Greenwich Civil Time (GCT)	10^h	10^h
Declination (δ) [American Nautical Almanac]	- 11°41′	+ 23°06′
$\cos\delta$	+0.9793	+0.9198
$\sin\delta$	- 0.2025	+0.3923
Greenwich hour angle (GHA) [American Nautical Almanac]	233°01′	329°04′
Longitude of station	118°10′	118°10′
Local hour angle (t)	114°51′	210°54′
cos t	- 0.4202	- 0.8581
cos z - from (4)	- 0.454	- 0.43

(Continued)

Sample Computation (concluded)

Item	g_m	g_s
Horizontal parallax of Moon (p) [American Ephemeris]	56′13″	. . . . .
sin p - from Table 2	+0.0164	. . . . .
$\sin^3 p$ - from Table 2	43.71×10^{-7}	. . . . .
$\alpha = c \sin p$	+0.0163	. . . . .
Radius vector of the Earth (D) [American Ephemeris]	. . . . .	1.0167
D^{-3} - from Table 3	. . . . .	0.9516
f - from Table 1, using closest α)	-0.460×10^4	-1.1×10^{-2}
g (in milligals)	-0.020	-0.010
g_t (to be applied to observed gravity)	-0.030	

Appendix--Primary astronomical constants

K_e	$-M_e\gamma/r_e^2 = -979.818$ gals [unpublished data of S. Herrick, Astron. Dept., U.C.L.A., Los Angeles, Calif.].
r_e	Radius of Earth at equator = 6.378388×10^8 cm [HAYFORD, 1910, p. 77].
r_p	Radius of Earth at poles = 6.356909×10^8 cm [HAYFORD, 1910, p. 72].
$\overline{R}$	Mean distance to Sun = 1.495000×10^{13} cm [HODGEMAN, 1947].
γ	$(6.670 \pm 0.002) \times 10^{-8}$ dynes cm²/gm² [HEYL, 1930].
M_m/M_e	$(1.23045 \pm 0.00032) \times 10^{-2}$ [SPENCER JONES, 1941].
M_s/M_e	3.334592×10^5 [CLEMENCE, 1948].

Derived constants

K_m	$K_e\ M_m/M_e = -1.20562 \times 10^4$ milligals
K_s	$K_e\ M_s/M_e\ (\overline{r}_e/R)^3 = -2.53745 \times 10^{-2}$ milligals
M_e	Mass of Earth = $(5.976 \pm 0.004) \times 10^{27}$ gm
M_m	Mass of Moon = 7.3537×10^{25} gm
$(\overline{r_e/R})$	4.26648×10^{-5} [CLEMENCE, 1948].
$(\overline{r_e/R})^3$	7.76621×10^{-14} [CLEMENCE, 1948].
C^2	$(1 - 0.01340199 \sin^2\phi)/(1 - 0.00672360 \sin^2\phi)$

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Table 1--Table of f (cos z, α, K)

Cos z	Sun	Moon																	
	K_s = -2.53745 $\times 10^{-2}$ milligals α = 4.25 $\times 10^{-5}$	K_m = - 1.20562 × 10^4 milligals																	
		α = 0.0150						α = 0.0165						α = 0.0180					
	$10^2 f$	$10^{-4} f$						$10^{-4} f$						$10^{-4} f$					
			0	2	4	6	8		0	2	4	6	8		0	2	4	6	8
-1.00	5.07458	2.3	5803	4421	3046	1664	0289	2.3	5286	3905	2531	1165	9791	2.3	4768	3395	2028	0662	9302
-0.99	4.92311	2.2	8923	7549	6182	4816	3458	2.2	8425	7066	5707	4348	2989	2.2	7943	6583	5230	3877	2524
-0.98	4.77316	2.2	2099	0741	*9391	*8032	*6690	2.2	1637	0285	*8933	*7589	*6244	2.2	1178	*9831	*8492	*7152	*5813
-0.97	4.62474	2.1	5340	3998	2655	1321	*9979	2.1	4907	3570	2233	0903	*9573	2.1	4480	3147	1814	0488	*9162
-0.96	4.47784	2.0	8645	7318	5992	4666	3340	2.0	8243	6921	5598	4276	2961	2.0	7842	6523	5203	3890	2578
-0.95	4.33246	2.0	2022	0704	*9385	*8075	*6765	2.0	1645	0330	*9022	*7714	*6414	2.0	1265	*9959	*8659	*7353	*6054
-0.94	4.18861	1.9	5463	4153	2851	1557	0255	1.9	5106	3805	2512	1219	*9925	1.9	4761	3462	2169	0883	*9597
-0.93	4.04627	1.8	8961	7667	6381	5095	3809	1.8	8639	7353	6067	4781	3510	1.8	8311	7032	5753	4473	3201
-0.92	3.90546	1.8	2531	1253	*9975	*8705	*7435	1.8	2231	0960	*9689	*8417	*7153	1.8	1935	0662	*9396	*8131	*6871
-0.91	3.76617	1.7	6165	4895	3633	2380	1118	1.7	5889	4625	3368	2111	0862	1.7	5612	4359	3107	1854	0609
-0.90	3.62840	1.6	9864	8610	7364	6110	4873	1.6	9612	8363	7121	5879	4637	1.6	9363	8117	6878	5639	4406
-0.89	3.49216	1.6	3627	2389	1151	*9913	*8684	1.6	3402	2160	0932	*9704	*8477	1.6	3167	1942	0709	*9490	*8264
-0.88	3.35743	1.5	7454	6232	5011	3789	2567	1.5	7249	6029	4809	3596	2376	1.5	7045	5826	4614	3402	2189
-0.87	3.22423	1.5	1354	0140	*8926	*7721	*6515	1.5	1170	*9957	*8752	*7546	*6348	1.5	0984	*9778	*8579	*7380	*6181
-0.86	3.09255	1.4	5309	4112	2914	1725	0527	1.4	5149	3951	2760	1569	0385	1.4	4989	3797	2605	1419	0234
-0.85	2.96239	1.3	9338	8156	6966	5785	4603	1.3	9194	8011	6834	5658	4481	1.3	9055	7876	6697	5525	4353
-0.84	2.83375	1.3	3430	2257	1083	*9918	*8752	1.3	3305	2136	0974	*9805	*8643	1.3	3188	2022	0857	*9698	*8539
-0.83	2.70664	1.2	7587	6429	5272	4115	2965	1.2	7489	6327	5173	4025	2871	1.2	7380	6228	5083	3931	2786
-0.82	2.58105	1.2	1816	0666	*9517	*8376	*7243	1.2	1731	0584	*9444	*8304	*7172	1.2	1647	0502	*9370	*8231	*7099
-0.81	2.45698	1.1	6101	4968	3835	2709	1584	1.1	6039	4907	3774	2656	1531	1.1	5967	4842	3717	2598	1480
-0.80	2.33443	1.1	0459	*9334	*8216	*7107	*5990	1.1	0413	*9295	*8177	*7066	*5956	1.1	0361	*9249	*8137	*7026	*5920
-0.79	2.21340	1.0	4881	3772	2671	1561	0466	1.0	4845	3742	2646	1542	0446	1.0	4815	3717	2618	1520	0428
-0.78	2.09390	0.9	9367	8274	7181	6096	5003	0.9	9350	8262	7173	6084	5003	0.9	9336	8251	7166	6081	5003
-0.77	1.97592	0.9	3926	2841	1764	0687	*9610	0.9	3921	2847	1766	0699	*9625	0.9	3924	2846	1774	0703	*9638
-0.76	1.85946	0.8	8541	7472	6411	5350	4289	0.8	8558	7491	6432	5373	4313	0.8	8573	7515	6456	5398	4340
-0.75	1.74452	0.8	3228	2175	1122	0077	*9024	0.8	3261	2209	1156	0112	*9067	0.8	3288	2243	1199	0154	*9109
-0.74	1.63110	0.7	7988	6943	5906	4869	3832	0.7	8029	6992	5954	4924	3894	0.7	8071	7039	6001	4976	3945
-0.73	1.51921	0.7	2803	1775	0754	*9725	*8712	0.7	2863	1840	0817	*9794	*8779	0.7	2920	1895	0877	*9859	*8848
-0.72	1.40884	0.6	7692	6679	5666	4653	3649	0.6	7763	6748	5739	4731	3730	0.6	7830	6825	5813	4809	3811
-0.71	1.29999	0.6	2644	1639	0643	*9646	*8657	0.6	2729	1728	0734	*9740	*8747	0.6	2813	1815	0817	*9826	*8841
-0.70	1.19266	0.5	7669	6680	5692	4711	3730	0.5	7760	6774	5795	4808	3836	0.5	7856	6872	5887	4909	3938
-0.69	1.08686	0.5	2750	1777	0806	*9832	*8868	0.5	2857	1886	0914	*9949	*8985	0.5	2967	1996	1025	0060	*9102
-0.68	0.98258	0.4	7903	6947	5982	5026	4077	0.4	8020	7063	6106	5156	4199	0.4	8138	7180	6229	5278	4327
-0.67	0.87982	0.4	3129	2181	1232	0292	*9351	0.4	3256	2306	1364	0421	*9486	0.4	3382	2438	1493	0556	*9625
-0.66	0.77858	0.3	8411	7479	6546	5622	4690	0.3	8551	7615	6687	5759	4839	0.3	8687	7756	6832	5907	4983
-0.65	0.67886	0.3	3765	2849	1933	1017	0100	0.3	3918	2997	2077	1163	0257	0.3	4065	3148	2230	1319	0408
-0.64	0.58067	0.2	9192	8284	7384	6475	5575	0.2	9344	8438	7539	6641	5742	0.2	9504	8600	7696	6798	5901
-0.63	0.48400	0.2	4683	3791	2899	2007	1122	0.2	4843	3952	3060	2176	1292	0.2	5010	4119	3228	2344	1460
-0.62	0.38885	0.2	0238	*9354	*8478	*7602	*6734	0.2	0408	*9531	*8654	*7777	*6908	0.2	0583	*9705	*8828	*7957	*7086
-0.61	0.29522	0.1	5866	4998	4130	3270	2410	0.1	6038	5176	4314	3452	2597	0.1	6222	5358	4494	3637	2780
-0.60	0.20311	0.1	1558	0698	*9854	*9002	*8158	0.1	1742	0887	0040	*9192	*8344	0.1	1922	1072	0228	*9384	*8540
-0.59	0.11253	0.0	7314	6470	5634	4798	3971	0.0	7504	6664	5831	4998	4165	0.0	7696	6859	6028	5191	4360
-0.58	0.02347	0.0	3143	2316	1487	0667	*0153	0.0	3339	2514	1688	0870	0051	0.0	3536	2713	1889	1072	0255
-0.57	-0.06407	-0.0	0964	1776	2588	3392	4204	-0.0	0760	1571	2382	3186	3990	-0.0	0556	1366	2177	2981	3784
-0.56	-0.15009	-0.0	4999	5803	6599	7394	8182	-0.0	4793	5590	6386	7183	7972	-0.0	4581	5386	6175	6966	7756
-0.55	-0.23458	-0.0	8970	9757	*0537	*1317	*2096	-0.0	8761	9543	*0324	*1106	*1881	-0.0	8547	9330	*0107	*0891	*1668
-0.54	-0.31756	-0.1	2876	3648	4411	5183	5946	-0.1	2655	3430	4197	4964	5724	-0.1	2438	3208	3978	4742	5506
-0.53	-0.39900	-0.1	6710	7465	8221	8976	9734	-0.1	6484	7244	7997	8749	9502	-0.1	6262	7019	7776	8526	9277
-0.52	-0.47893	-0.2	0471	1219	1958	2698	3437	-0.2	0247	0992	1730	2468	3206	-0.2	0020	0763	1507	2244	2980
-0.51	-0.55734	-0.2	4169	4900	5631	6355	7078	-0.2	3944	4675	5398	6129	6845	-0.2	3711	4447	5171	5894	6617
-0.50	-0.63422	-0.2	7802	8517	9232	9940	*0655	-0.2	7569	8285	9001	9709	*0418	-0.2	7341	8057	8767	9477	*0187
-0.49	-0.70958	-0.3	1362	2061	2761	3460	4159	-0.3	1127	1828	2530	3231	3925	-0.3	0897	-1594	2297	2994	3690
-0.48	-0.78342	-0.3	4860	5542	6233	6916	7599	-0.3	4620	5306	5993	6680	7360	-0.3	4380	5070	5760	6443	7126
-0.47	-0.85574	-0.3	8274	8950	9625	*0300	*0967	-0.3	8039	8719	9391	*0063	*0728	-0.3	7803	8479	9156	9826	*0489
-0.46	-0.92653	-0.4	1634	2293	2952	3611	4262	-0.4	1393	2058	2715	3373	4031	-0.4	1159	1822	2478	3134	3791
-0.45	-0.99580	-0.4	4913	5564	6215	6858	7493	-0.4	4681	5331	5974	6617	7260	-0.4	4440	5090	5740	6383	7019
-0.44	-1.06355	-0.4	8136	8771	9406	*0033	*0660	-0.4	7896	8532	9167	9796	*0424	-0.4	7662	8292	8928	9558	*0187
-0.43	-1.12978	-0.5	1287	1906	2525	3144	3755	-0.5	1045	1666	2287	2901	3515	-0.5	0810	1433	2049	2666	3282
-0.42	-1.19449	-0.5	4365	4968	5579	6182	6777	-0.5	4129	4735	5342	5941	6540	-0.5	3891	4494	5104	5706	6302
-0.41	-1.25767	-0.5	7379	7966	8561	9148	9734	-0.5	7139	7731	8323	8915	9499	-0.5	6905	7495	8091	8674	9263

(Continued)

Table 1--Table of f (cos z, α, K) (continued)

Cos z	Sun	Moon																	
	K_s = -2.53745 $\times 10^{-2}$ milligals α = 4.25 $\times 10^{-5}$	K_m = - 1.20562 × 10^4 milligals																	
		α = 0.0150						α = 0.0165						α = 0.0180					
	$10^2 f$	$10^{-4} f$						$10^{-4} f$						$10^{-4} f$					
			0	2	4	6	8		0	2	4	6	8		0	2	4	6	8
-0.40	-1.31933	-0.6	0321	0900	1479	2049	2620	-0.6	0084	0661	1238	1815	2385	-0.5	9846	*0428	*1004	*1580	*2150
-0.39	-1.37947	-0.6	3191	3761	4324	4878	5441	-0.6	2955	3525	4088	4650	5206	-0.6	2719	3288	3851	4414	4976
-0.38	-1.43809	-0.6	5996	6550	7097	7643	8190	-0.6	5761	6316	6864	7412	7960	-0.6	5532	6081	6631	7180	7729
-0.37	-1.49518	-0.6	8728	9267	9805	*0336	*0866	-0.6	8501	9042	9575	*0109	*0642	-0.6	8265	8807	9343	9879	*0408
-0.36	-1.55075	-0.7	1397	1919	2442	2964	3479	-0.7	1168	1694	2213	2732	3251	-0.7	0937	1466	1989	2505	3027
-0.35	-1.60480	-0.7	3993	4499	5014	5512	6018	-0.7	3762	4273	4785	5289	5793	-0.7	3536	4052	4561	5070	5572
-0.34	-1.65733	-0.7	6517	7015	7505	8004	8486	-0.7	6297	6794	7284	7781	8270	-0.7	6075	6570	7066	7555	8050
-0.33	-1.70833	-0.7	8976	9458	9941	*0415	*0889	-0.7	8753	9242	9717	*0199	*0674	-0.7	8533	9022	9504	9979	*0455
-0.32	-1.75782	-0.8	1363	1829	2296	2762	3220	-0.8	1149	1617	2084	2545	3005	-0.8	0931	1399	1868	2330	2793
-0.31	-1.80578	-0.8	3678	4136	4586	5036	5486	-0.8	3465	3926	4379	4825	5278	-0.8	3255	3710	4166	4614	5063
-0.30	-1.85221	-0.8	5929	6371	6805	7247	7673	-0.8	5716	6162	6600	7038	7470	-0.8	5512	5954	6396	6831	7267
-0.29	-1.89713	-0.8	8107	8533	8959	9377	9795	-0.8	7901	8332	8756	9179	9596	-0.8	7695	8124	8553	8975	9397
-0.28	-1.94052	-0.9	0213	0630	1040	1442	1852	-0.9	0012	0429	0838	1247	1656	-0.8	9812	*0227	*0643	*1051	*1460
-0.27	-1.98240	-0.9	2254	2648	3050	3444	3829	-0.9	2058	2460	2855	3249	3644	-0.9	1862	2263	2659	3054	3449
-0.26	-2.02274	-0.9	4223	4601	4987	5365	5742	-0.9	4031	4418	4798	5178	5558	-0.9	3837	4226	4608	4989	5371
-0.25	-2.06157	-0.9	6120	6490	6860	7221	7583	-0.9	5931	6303	6676	7041	7407	-0.9	5746	6121	6490	6858	7220
-0.24	-2.09887	-0.9	7945	8298	8660	9006	9359	-0.9	7765	8123	8481	8832	9182	-0.9	7582	7943	8298	8653	9001
-0.23	-2.13466	-0.9	9705	*0042	*0388	*0726	*1055	-0.9	9526	9869	*0213	*0549	*0885	-0.9	9350	9698	*0040	*0381	*0716
-0.22	-2.16891	-1.0	1393	1714	2044	2365	2687	-1.0	1221	1550	1879	2200	2522	-1.0	1051	1379	1707	2036	2357
-0.21	-2.20165	-1.0	3008	3322	3635	3941	4246	-1.0	2843	3157	3471	3778	4093	-1.0	2679	2993	3308	3623	3931
-0.20	-2.23286	-1.0	4551	4849	5146	5444	5733	-1.0	4392	4699	4999	5291	5583	-1.0	4239	4541	4842	5137	5431
-0.19	-2.26256	-1.0	6022	6312	6593	6874	7156	-1.0	5875	6160	6445	6730	7008	-1.0	5726	6014	6302	6584	6865
-0.18	-2.29073	-1.0	7429	7702	7975	8241	8506	-1.0	7286	7563	7834	8097	8367	-1.0	7139	7414	7689	7957	8224
-0.17	-2.31737	-1.0	8763	9020	9277	9527	9776	-1.0	8623	8886	9141	9397	9646	-1.0	8486	8747	9008	9263	9517
-0.16	-2.34250	-1.1	0025	0274	0515	0748	0989	-1.0	9894	*0143	*0384	*0625	*0859	-1.0	9765	*0013	*0254	*0495	*0736
-0.15	-2.36610	-1.1	1214	1448	1673	1898	2123	-1.1	1092	1326	1553	1779	1998	-1.1	0971	1205	1433	1661	1882
-0.14	-2.38818	-1.1	2340	2557	2766	2975	3184	-1.1	2225	2437	2656	2861	3073	-1.1	2103	2324	2538	2752	2960
-0.13	-2.40874	-1.1	3385	3585	3786	3979	4172	-1.1	3277	3482	3679	3876	4074	-1.1	3168	3375	3576	3770	3965
-0.12	-2.42778	-1.1	4365	4550	4735	4920	5097	-1.1	4264	4454	4636	4819	5002	-1.1	4159	4353	4541	4721	4902
-0.11	-2.44529	-1.1	5273	5442	5619	5780	5948	-1.1	5177	5352	5520	5696	5856	-1.1	5083	5257	5431	5599	5766
-0.10	-2.46128	-1.1	6109	6270	6423	6575	6728	-1.1	6024	6178	6339	6492	6646	-1.1	5934	6095	6255	6409	6563
-0.09	-2.47575	-1.1	6873	7017	7162	7299	7435	-1.1	6792	6936	7084	7223	7362	-1.1	6711	6858	7005	7146	7287
-0.08	-2.48869	-1.1	7564	7693	7821	7950	8070	-1.1	7493	7625	7756	7880	8005	-1.1	7421	7555	7682	7809	7936
-0.07	-2.50012	-1.1	8183	8303	8416	8520	8633	-1.1	8122	8238	8355	8465	8575	-1.1	8057	8178	8291	8405	8512
-0.06	-2.51002	-1.1	8737	8834	8938	9027	9123	-1.1	8677	8779	8881	8976	9071	-1.1	8620	8727	8827	8928	9021
-0.05	-2.51840	-1.1	9212	9300	9380	9469	9541	-1.1	9166	9254	9342	9422	9503	-1.1	9115	9202	9289	9376	9457
-0.04	-2.52525	-1.1	9622	9694	9758	9831	9895	-1.1	9576	9649	9722	9795	9861	-1.1	9537	9611	9685	9752	9825
-0.03	-2.53058	-1.1	9951	*0007	*0064	*0120	*0168	-1.1	9919	9977	*0036	*0087	*0138	-1.1	9886	9946	*0006	*0060	*0113
-0.02	-2.53439	-1.2	0216	0257	0297	0337	0369	-1.2	0189	0233	0277	0314	0350	-1.2	0167	0214	0254	0294	0334
-0.01	-2.53668	-1.2	0401	0433	0458	0482	0506	-1.2	0387	0416	0445	0474	0496	-1.2	0368	0401	0435	0462	0482
0.00	-2.53745	-1.2	0522	0538	0546	0554	0562	-1.2	0511	0533	0540	0555	0562	-1.2	0502	0522	0535	0549	0555
0.01	-2.53669	-1.2	0570	0570	0562	0562	0554	-1.2	0569	0569	0569	0562	0555	-1.2	0562	0569	0569	0569	0562
0.02	-2.53442	-1.2	0538	0522	0506	0490	0466	-1.2	0547	0533	0518	0504	0482	-1.2	0555	0542	0529	0515	0495
0.03	-2.53061	-1.2	0441	0409	0377	0345	0305	-1.2	0452	0430	0401	0365	0328	-1.2	0468	0448	0415	0388	0354
0.04	-2.52529	-1.2	0265	0224	0176	0128	0080	-1.2	0292	0248	0204	0160	0109	-1.2	0314	0274	0234	0187	0140
0.05	-2.51844	-1.2	0023	*9967	*9903	*9839	*9774	-1.2	0058	*9999	*9941	*9875	*9817	-1.2	0086	0033	*9973	*9912	*9852
0.06	-2.51008	-1.1	9702	9630	9557	9477	9397	-1.1	9744	9678	9605	9524	9444	-1.1	9785	9718	9644	9571	9490
0.07	-2.50018	-1.1	9316	9228	9139	9043	8955	-1.1	9364	9276	9188	9101	9006	-1.1	9410	9330	9243	9155	9062
0.08	-2.48877	-1.1	8850	8754	8649	8537	8432	-1.1	8911	8808	8706	8604	8494	-1.1	8968	8867	8767	8660	8553
0.09	-2.47583	-1.1	8320	8199	8078	7958	7837	-1.1	8385	8268	8151	8027	7910	-1.1	8445	8332	8218	8097	7977
0.10	-2.46137	-1.1	7709	7580	7443	7307	7170	-1.1	7778	7654	7522	7384	7245	-1.1	7849	7722	7595	7461	7327
0.11	-2.44539	-1.1	7026	6881	6736	6583	6431	-1.1	7106	6960	6814	6667	6514	-1.1	7186	7046	6898	6751	6604
0.12	-2.42789	-1.1	6270	6109	5948	5780	5611	-1.1	6361	6200	6039	5878	5710	-1.1	6449	6289	6128	5967	5800
0.13	-2.40886	-1.1	5442	5265	5088	4912	4727	-1.1	5542	5367	5192	5009	4826	-1.1	5632	5465	5291	5110	4929
0.14	-2.38831	-1.1	4542	4349	4164	3963	3770	-1.1	4644	4461	4264	4074	3876	-1.1	4748	4561	4373	4179	3985
0.15	-2.36634	-1.1	3569	3360	3159	2942	2734	-1.1	3679	3474	3270	3058	2853	-1.1	3790	3589	3382	3174	2967
0.16	-2.34365	-1.1	2516	2299	2074	1857	1634	-1.1	2634	2422	2196	1977	1750	-1.1	2752	2538	2317	2096	1875
0.17	-2.31753	-1.1	1399	1166	0935	0684	0443	-1.1	1524	1290	1056	0815	0574	-1.1	1647	1413	1185	0944	0709
0.18	-2.29089	-1.1	0202	*9953	*9703	*9446	*9189	-1.1	0332	0084	*9836	*9587	*9331	-1.1	0462	0220	*9973	*9718	*9464
0.19	-2.26273	-1.0	8932	8667	8401	8136	7863	-1.0	9066	8813	8542	8279	8009	-1.0	9209	8948	8687	8419	8151

(Continued)

Table 1--Table of f (cos z, α, K) (continued)

Cos z	Sun	Moon																	
	K_s = -2.53745 $\times 10^{-2}$ milligals α = 4.25 $\times 10^{-5}$	K_m = - 1.20562 × 10^4 milligals																	
		α = 0.0150						α = 0.0165						α = 0.0180					
	$10^2 f$	$10^{-4} f$						$10^{-4} f$						$10^{-4} f$					
			0	2	4	6	8		0	2	4	6	8		0	2	4	6	8
0.20	-2.23305	-1.0	7590	7308	7027	6746	6456	-1.0	7731	7461	7176	6898	6613	-1.0	7883	7608	7327	7046	6764
0.21	-2.20184	-1.0	6167	5878	5580	5283	4985	-1.0	6321	6036	5737	5444	5145	-1.0	6476	6188	5894	5599	5298
0.22	-2.16911	-1.0	4680	4375	4061	3748	3434	-1.0	4838	4531	4224	3910	3596	-1.0	4996	4695	4387	4078	3764
0.23	-2.13486	-1.0	3113	2791	2470	2140	1811	-1.0	3281	2960	2638	2310	1981	-1.0	3449	3127	2806	2478	2150
0.24	-2.09908	-1.0	1473	1135	0798	0452	0107	-1.0	1645	1309	0973	0629	0286	-1.0	1821	1486	1145	0810	0462
0.25	-2.06179	-0.9	9761	9407	9054	8700	8338	-0.9	9942	9592	9233	8883	8517	-1.0	0120	*9772	*9417	*9062	*8700
0.26	-2.02297	-0.9	7977	7607	7237	6868	6490	-0.9	8159	7794	7421	7056	6676	-0.9	8338	7977	7608	7240	6865
0.27	-1.98262	-0.9	6112	5726	5348	4955	4569	-0.9	6303	5924	5536	5149	4762	-0.9	6490	6115	5726	5344	4956
0.28	-1.94076	-0.9	4175	3781	3379	2977	2568	-0.9	4367	3973	3578	3176	2767	-0.9	4567	4172	3770	3375	2973
0.29	-1.89737	-0.9	2166	1756	1338	0920	0502	-0.9	2365	1956	1539	1123	0706	-0.9	2565	2156	1741	1326	0910
0.30	-1.85246	-0.9	0076	*9650	*9224	*8790	*8356	-0.9	0283	*9859	*9428	*8997	*8566	-0.9	0488	0067	*9638	*9209	*8774
0.31	-1.80603	-0.8	7914	7472	7030	6580	6129	-0.8	8127	7689	7243	6797	6344	-0.8	8338	7896	7454	7012	6564
0.32	-1.75807	-0.8	5679	5221	4763	4305	3839	-0.8	5899	5438	4985	4518	4057	-0.8	6108	5653	5197	4735	4273
0.33	-1.70860	-0.8	3373	2898	2424	1950	1468	-0.8	3590	3122	2647	2172	1690	-0.8	3811	3342	2866	2391	1915
0.34	-1.65760	-0.8	0986	0495	0013	*9515	*9024	-0.8	1208	0725	0236	*9739	*9249	-0.8	1433	0944	0455	*9966	*9477
0.35	-1.60507	-0.7	8526	8020	7521	7015	6501	-0.7	8753	8248	7744	7240	6729	-0.7	8975	8479	7977	7468	6959
0.36	-1.55103	-0.7	5986	5472	4949	4427	3905	-0.7	6217	5706	5187	4661	4135	-0.7	6450	5934	5418	4896	4373
0.37	-1.49546	-0.7	3374	2844	2313	1775	1236	-0.7	3609	3082	2549	2008	1468	-0.7	3844	3315	2779	2243	1708
0.38	-1.43837	-0.7	0690	0143	*9596	*9042	*8487	-0.7	0927	0379	*9831	*9283	*8728	-0.7	1165	0616	0067	*9517	*8961
0.39	-1.37975	-0.6	7925	7370	6799	6237	5666	-0.6	8165	7602	7040	6477	5907	-0.6	8406	7843	7280	6718	6148
0.40	-1.31962	-0.6	5087	4517	3938	3351	2765	-0.6	5330	4753	4176	3591	3006	-0.6	5572	4996	4420	3838	3255
0.41	-1.25796	-0.6	2178	1583	0988	0394	*9791	-0.6	2422	1830	1238	0639	0040	-0.6	2665	2076	1480	0884	0281
0.42	-1.19476	-0.5	9188	8585	7974	7363	6745	-0.5	9433	8827	8220	7607	6986	-0.5	9678	9075	8466	7850	7233
0.43	-1.13007	-0.5	6126	5507	4880	4253	3618	-0.5	6372	5751	5122	4494	3866	-0.5	6617	5994	5371	4742	4112
0.44	-1.06384	-0.5	2983	2348	1705	1062	0419	-0.5	3230	2594	1951	1308	0665	-0.5	3476	2840	2203	1560	0911
0.45	-0.99609	-0.4	9768	9117	8458	7799	7140	-0.5	0015	*9365	*8707	*8049	*7385	-0.5	0261	*9611	*8955	*8298	*7635
0.46	-0.92682	-0.4	6473	5806	5138	4463	3788	-0.4	6720	6055	5382	4710	4038	-0.4	6972	6303	5633	4956	4280
0.47	-0.85603	-0.4	3105	2422	1739	1047	0356	-0.4	3351	2672	1985	1298	0604	-0.4	3603	2920	2230	1547	0850
0.48	-0.78371	-0.3	9665	8966	8266	7559	6852	-0.3	9910	9208	8507	7806	7097	-0.4	0154	*9457	*8754	*8051	*7347
0.49	-0.70987	-0.3	6144	5429	4714	3990	3267	-0.3	6388	5672	4956	4240	3516	-0.3	6631	5921	5204	4481	3757
0.50	-0.63450	-0.3	2544	1820	1089	0349	*9610	-0.3	2786	2062	1332	0594	*9856	-0.3	3034	2304	1574	0837	0100
0.51	-0.55762	-0.2	8871	8131	7384	6628	5881	-0.2	9110	8372	7620	6874	6114	-0.2	9357	8613	7863	7113	6356
0.52	-0.47921	-0.2	5125	4362	3598	2834	2063	-0.2	5362	4602	3835	3075	2300	-0.2	5599	4842	4079	3309	2545
0.53	-0.39928	-0.2	1291	0520	*9740	*8960	*8181	-0.2	1533	0759	*9977	*9196	*8413	-0.2	1768	0991	0214	*9431	*8647
0.54	-0.31782	-0.1	7393	6597	5810	5014	4210	-0.1	7624	6835	6038	5242	4446	-0.1	7857	7066	6276	5479	4675
0.55	-0.23485	-0.1	3406	2603	1799	0987	0167	-0.1	3642	2831	2027	1216	0398	-0.1	3871	3068	2257	1440	0623
0.56	-0.15035	-0.0	9356	8536	7708	6880	6052	-0.0	9579	8754	7935	7102	6277	-0.0	9806	8982	8158	7327	6497
0.57	-0.06432	-0.0	5216	4380	3545	2701	1857	-0.0	5436	4603	3763	2915	2075	-0.0	5660	4822	3985	3141	2291
0.58	0.02322	-0.0	1006	0153	*0699	*1559	*2419	-0.0	1220	0373	*0482	*1344	*2207	-0.0	1440	0589	*0268	*1132	*1996
0.59	0.11229	0.0	3279	4147	5015	5891	6768	0.0	3069	3938	4808	5685	6561	0.0	2860	3731	4601	5479	6356
0.60	0.20288	0.0	7644	8528	9412	*0304	*1196	0.0	7446	8330	9214	*0105	*0997	0.0	7234	8125	9009	9899	*0797
0.61	0.29499	0.1	2088	2989	3889	4797	5697	0.1	1896	2794	3693	4599	5505	0.1	1695	2592	3496	4407	5318
0.62	0.38863	0.1	6613	7522	8438	9362	*0287	0.1	6418	7332	8252	9173	*0101	0.1	6229	7147	8064	8989	9913
0.63	0.48379	0.2	1211	2135	3068	4008	4940	0.2	1029	1957	2892	3827	4770	0.2	0844	1775	2706	3650	4588
0.64	0.58047	0.2	5889	6829	7777	8726	9682	0.2	5713	6655	7605	8555	9512	0.2	5532	6483	7435	8386	9343
0.65	0.67867	0.3	0639	1596	2560	3524	4497	0.3	0469	1434	2398	3370	4342	0.3	0301	1266	2237	3201	4179
0.66	0.77840	0.3	5469	6442	7422	8403	9392	0.3	5314	6293	7272	8251	9245	0.3	5157	6135	7113	8104	9089
0.67	0.87965	0.4	0380	1369	2365	3362	4359	0.4	0231	1225	2219	3220	4221	0.4	0080	1078	2076	3081	4086
0.68	0.98242	0.4	5363	6376	7381	8394	9414	0.4	5229	6237	7253	8269	9284	0.4	5090	6102	7120	8138	9156
0.69	1.08672	0.5	0427	1456	2477	3505	4542	0.5	0307	1330	2360	3391	4421	0.5	0181	1205	2237	3268	4306
0.70	1.19254	0.5	5571	6616	7653	8698	9742	0.5	5459	6503	7548	8593	9638	0.5	5345	6390	7434	8486	9538
0.71	1.29988	0.6	0795	1848	2909	3970	5031	0.6	0697	1750	2809	3876	4935	0.6	0589	1647	2712	3777	4849
0.72	1.40874	0.6	6092	7169	8238	9315	*0392	0.6	6010	7076	8158	9232	*0313	0.6	5914	6992	8071	9149	*0234
0.73	1.51913	0.7	1477	2562	3647	4740	5833	0.7	1402	2491	3579	4675	5771	0.7	1319	2411	3509	4601	5706
0.74	1.63104	0.7	6927	8036	9137	*0246	*1355	0.7	6867	7971	9081	*0192	*1303	0.7	6806	7917	9022	*0140	*1252
0.75	1.74447	0.8	2464	3582	4699	5824	6949	0.8	2421	3539	4664	5789	6914	0.8	2371	3496	4621	5746	6885
0.76	1.85943	0.8	8083	9216	*0349	*1482	*2634	0.8	8047	9187	*0327	*1466	*2614	0.8	8017	9156	*0301	*1440	*2592
0.77	1.97591	0.9	3773	4922	6072	7229	8387	0.9	3761	4908	6062	7224	8386	0.9	3744	4896	6054	7213	8379
0.78	2.09391	0.9	9644	*0709	*1875	*3048	*4222	0.9	9648	*0717	*1886	*3055	*4239	0.9	9551	*0716	*1895	*3067	*4253
0.79	2.21343	1.0	5395	6577	7758	8940	*0129	1.0	5415	6599	7782	8973	*0164	1.0	5431	6624	7809	9001	*0200

(Continued)

Table 1--Table of f (cos z, α, K) (concluded)

Cos z	Sun	Moon																	
	K_s = -2.53745 ×10^{-2} milligals α = 4.25 ×10^{-5}	K_m = - 1.20562 × 10^4 milligals																	
		α = 0.0150						α = 0.0165						α = 0.0180					
	$10^2 f$	$10^{-4} f$						$10^{-4} f$						$10^{-4} f$					
			0	2	4	6	8		0	2	4	6	8		0	2	4	6	8
0.80	2.33448	1.1	1327	2516	3722	4920	6125	1.1	1363	2561	3767	4972	6178	1.1	1399	2605	3811	5016	6228
0.81	2.45705	1.1	7331	8545	9758	*0980	*2202	1.1	7391	8604	9824	*1044	*2272	1.1	7447	8666	9886	*1111	*2344
0.82	2.58114	1.2	3423	4653	5875	7113	8350	1.2	3499	4727	5962	7204	8446	1.2	3576	4808	6048	7287	8532
0.83	2.70676	1.2	9588	*0834	*2080	*3325	*4579	1.2	9688	*0930	*2187	*3437	*4693	1.2	9785	*1031	*2290	*3549	*4808
0.84	2.83390	1.3	5833	7095	8357	9619	*0889	1.3	5957	7221	8486	9757	*1028	1.3	6074	7340	8613	9885	*1165
0.85	2.96256	1.4	2159	3437	4715	5993	7279	1.4	2300	3578	4864	6150	7436	1.4	2444	3723	5016	6302	7595
0.86	3.09274	1.4	8565	9859	*1153	*2447	*3749	1.4	8730	*0023	*1324	*2624	*3932	1.4	8894	*0193	*1500	*2806	*4112
0.87	3.22445	1.5	5051	6361	7671	8981	*0299	1.5	5240	6548	7863	9186	*0508	1.5	5425	6744	8063	9383	*0709
0.88	3.35768	1.6	1617	2944	4270	5596	6930	1.6	1831	3161	4490	5820	7157	1.6	2042	3375	4708	6047	7387
0.89	3.49243	1.6	8264	9607	*0949	*2291	*3641	1.6	8502	9846	*1191	*2542	*3894	1.6	8733	*0086	*1439	*2792	*4152
0.90	3.62871	1.7	4992	6342	7700	9067	*0425	1.7	5253	6612	7971	9338	*0711	1.7	5511	6878	8244	9617	*0990
0.91	3.76650	1.8	1791	3166	4540	5915	7297	1.8	2085	3459	4840	6221	7609	1.8	2370	3750	5136	6523	7916
0.92	3.90583	1.8	8680	*0070	*1460	*2851	*4249	1.8	8997	*0386	*1781	*3184	*4587	1.8	9309	*0709	*2109	*3515	*4922
0.93	4.04667	1.9	5648	7047	8453	9868	*1274	1.9	5990	7400	8810	*0228	*1645	1.9	6335	7748	9168	*0588	*2008
0.94	4.18904	2.0	2689	4111	5534	6957	8387	2.0	3063	4488	5920	7352	8784	2.0	3442	4868	6302	7742	9182
0.95	4.33293	2.0	9818	*1257	*2687	*4134	*5581	2.1	0224	1663	3110	4557	6003	2.1	0622	2075	3522	4975	6436
0.96	4.47834	2.1	7028	8474	9929	*1392	*2847	2.1	7457	8919	*0380	*1841	*3310	2.1	7896	9356	*0823	*2296	*3770
0.97	4.62528	2.2	4310	5780	7251	8722	*0201	2.2	4779	6255	7731	9207	*0690	2.2	5243	6724	8210	9697	*1184
0.98	4.77374	2.3	1680	3167	4654	6141	7636	2.3	2180	3671	5162	6660	8157	2.3	2678	4178	5679	7179	8686
0.99	4.92372	2.3	9131	*0634	*2129	*3640	*5151	2.3	9663	*1168	*2680	*4193	*5705	2.4	0193	1707	3227	4748	6268
1.00	5.07522	2.4	6662					2.4	7225					2.4	7795				

Table 2--Values of sin p and $\sin^3 p$ for various values of p

p=0°52′+S″			p=0°53′+S″			p=0°54′+S″			p=0°55′+S″			p=0°56′+S″			p=0°57′+S″			p=0°58′+S″			p=0°59′+S″		
S″	sin p 0.015	$\sin^3 p$ × 10^{-7}	S″	sin p 0.015	$\sin^3 p$ × 10^{-7}	S″	sin p 0.015	$\sin^3 p$ × 10^{-7}	S″	sin p 0.016	$\sin^3 p$ × 10^{-7}	S″	sin p 0.016	$\sin^3 p$ × 10^{-7}	S″	sin p 0.016	$\sin^3 p$ × 10^{-7}	S″	sin p 0.017	$\sin^3 p$ × 10^{-7}	S″	sin p 0.017	$\sin^3 p$ × 10^{-7}
0	13	34.63	0	42	36.67	0	71	38.77	0	00	40.96	0	29	43.23	0	58	45.58	0	87	48.01	0	16	50.53
1	13	34.66	1	42	36.67	1	71	38.77	1	00	40.96	1	29	43.23	1	58	45.58	1	88	48.10	1	17	50.61
2	14	34.70	2	43	36.74	2	72	38.83	2	01	41.04	2	30	43.31	2	59	45.66	2	88	48.10	2	17	50.61
3	14	34.73	3	43	36.74	3	72	38.85	3	01	41.04	3	30	43.31	3	59	45.66	3	89	48.18	3	18	50.71
4	15	34.77	4	44	36.81	4	73	38.92	4	02	41.11	4	31	43.39	4	60	45.74	4	89	48.18	4	18	50.71
5	15	34.80	5	44	36.81	5	73	38.92	5	02	41.11	5	31	43.39	5	60	45.74	5	89	48.18	5	19	50.80
6	15	34.80	6	45	36.88	6	74	39.00	6	03	41.19	6	32	43.47	6	61	45.83	6	90	48.27	6	19	50.80
7	16	34.87	7	45	36.88	7	74	39.00	7	03	41.19	7	32	43.47	7	61	45.83	7	90	48.27	7	20	50.88
8	16	34.87	8	46	36.95	8	75	39.07	8	04	41.27	8	33	43.55	8	62	45.91	8	91	48.35	8	20	50.88
9	17	34.94	9	46	36.95	9	75	39.07	9	04	41.27	9	33	43.55	9	62	45.91	9	91	48.35	9	21	50.97
10	17	34.94	10	46	36.95	10	76	39.14	10	05	41.35	10	34	43.63	10	63	45.99	10	92	48.44	10	21	50.97
11	18	35.00	11	47	37.02	11	76	39.14	11	05	41.35	11	34	43.63	11	63	45.99	11	92	48.44	11	21	50.97
12	18	35.00	12	47	37.02	12	77	39.22	12	06	41.42	12	35	43.71	12	64	46.07	12	93	48.53	12	22	51.06
13	19	35.08	13	48	37.09	13	77	39.22	13	06	41.42	13	35	43.71	13	64	46.07	13	93	48.53	13	22	51.06
14	19	35.08	14	48	37.09	14	78	39.29	14	07	41.50	14	36	43.79	14	65	46.16	14	94	48.61	14	23	51.15
15	20	35.15	15	49	37.17	15	78	39.29	15	07	41.50	15	36	43.79	15	65	46.16	15	94	48.61	15	23	51.15
16	20	35.18	16	49	37.17	16	78	39.29	16	08	41.58	16	37	43.87	16	66	46.24	16	95	48.70	16	24	51.24
17	21	35.21	17	50	37.24	17	79	39.37	17	08	41.58	17	37	43.87	17	66	46.24	17	95	48.70	17	24	51.24
18	21	35.24	18	50	37.24	18	79	39.37	18	09	41.66	18	38	43.95	18	67	46.32	18	96	48.78	18	25	51.33
19	22	35.26	19	51	37.31	19	80	39.44	19	09	41.66	19	38	43.95	19	67	46.32	19	96	48.78	19	25	51.33

(Continued)

Table 2--Values of sin p and $\sin^3 p$ for various values of p (concluded)

p=0°52′+S″			p=0°53′+S″			p=0°54′+S″			p=0°55′+S″			p=0°56′+S″			p=0°57′+S″			p=0°58′+S″			p=0°59′+S″		
S″	sin p 0.015	$\sin^3 p$ × 10^{-7}	S″	sin p 0.015	$\sin^3 p$ × 10^{-7}	S″	sin p 0.015	$\sin^3 p$ × 10^{-7}	S″	sin p 0.016	$\sin^3 p$ × 10^{-7}	S″	sin p 0.016	$\sin^3 p$ × 10^{-7}	S″	sin p 0.016	$\sin^3 p$ × 10^{-7}	S″	sin p 0.017	$\sin^3 p$ × 10^{-7}	S″	sin p 0.017	$\sin^3 p$ × 10^{-7}
20	22	35.29	20	51	37.31	20	80	39.44	20	10	41.73	20	39	44.03	20	68	46.41	20	97	48.87	20	26	51.42
21	23	35.33	21	52	37.38	21	81	39.52	21	10	41.73	21	39	44.03	21	68	46.41	21	97	48.87	21	26	51.42
22	23	35.36	22	52	37.38	22	81	39.52	22	10	41.73	22	40	44.11	22	69	46.49	22	98	48.96	22	27	51.51
23	24	35.40	23	53	37.46	23	82	39.59	23	11	41.81	23	40	44.11	23	69	46.49	23	98	48.96	23	27	51.51
24	24	35.43	24	53	37.46	24	82	39.59	24	11	41.81	24	41	44.19	24	70	46.57	24	99	49.04	24	28	51.60
25	25	35.47	25	54	37.53	25	83	39.67	25	12	41.89	25	41	44.19	25	70	46.57	25	99	49.04	25	28	51.60
26	25	35.50	26	54	37.53	26	83	39.67	26	12	41.89	26	42	44.27	26	71	46.66	26	100	49.13	26	29	51.69
27	26	35.54	27	55	37.60	27	84	39.74	27	13	41.97	27	42	44.27	27	71	46.66	27	100	49.13	27	29	51.69
28	26	35.57	28	55	37.60	28	84	39.74	28	13	41.97	28	42	44.27	28	72	46.74	28	101	49.22	28	30	51.78
29	27	35.61	29	56	37.66	29	85	39.82	29	14	42.04	29	43	44.35	29	72	46.74	29	101	49.22	29	30	51.78
30	27	35.64	30	56	37.67	30	85	39.82	30	14	42.04	30	43	44.35	30	73	46.83	30	02	49.30	30	31	51.87
31	28	35.68	31	57	37.75	31	86	39.89	31	15	42.12	31	44	44.43	31	73	46.83	31	02	49.30	31	31	51.87
32	28	35.71	32	57	37.75	32	86	39.89	32	15	42.12	32	44	44.43	32	73	46.83	32	03	49.39	32	32	51.96
33	29	35.75	33	58	37.82	33	87	39.97	33	16	42.20	33	45	44.51	33	74	46.91	33	03	49.39	33	32	51.96
34	29	35.78	34	58	37.82	34	87	39.97	34	16	42.20	34	45	44.51	34	74	46.91	34	04	49.48	34	33	52.05
35	30	35.82	35	59	37.89	35	88	40.05	35	17	42.28	35	46	44.60	35	75	46.99	35	04	49.48	35	33	52.05
36	30	35.85	36	59	37.89	36	88	40.05	36	17	42.28	36	46	44.60	36	75	46.99	36	05	49.56	36	34	52.14
37	30	35.85	37	60	37.96	37	89	40.12	37	18	42.36	37	47	44.68	37	76	47.08	37	05	49.56	37	34	52.14
38	31	35.92	38	60	37.96	38	89	40.12	38	18	42.36	38	47	44.68	38	76	47.08	38	05	49.56	38	35	52.23
39	31	35.92	39	61	38.04	39	90	40.20	39	19	42.44	39	48	44.76	39	77	47.16	39	06	49.65	39	35	52.23
40	32	35.99	40	61	38.04	40	90	40.20	40	19	42.44	40	48	44.76	40	77	47.16	40	06	49.65	40	36	52.32
41	32	35.99	41	62	38.11	41	91	40.27	41	20	42.52	41	49	44.84	41	78	47.25	41	07	49.74	41	36	52.32
42	33	36.06	42	62	38.11	42	91	40.27	42	20	42.52	42	49	44.84	42	78	47.25	42	07	49.74	42	37	52.41
43	33	36.06	43	62	38.11	43	92	40.35	43	21	42.59	43	50	44.92	43	79	47.33	43	08	49.83	43	37	52.41
44	34	36.13	44	63	38.18	44	92	40.35	44	21	42.59	44	50	44.92	44	79	47.33	44	08	49.83	44	37	52.41
45	34	36.13	45	63	38.18	45	93	40.43	45	22	42.67	45	51	45.00	45	80	47.42	45	09	49.91	45	38	52.50
46	35	36.20	46	64	38.26	46	93	40.43	46	22	42.67	46	51	45.00	46	80	47.42	46	09	49.91	46	38	52.50
47	35	36.20	47	64	38.26	47	94	40.50	47	23	42.75	47	52	45.08	47	81	47.50	47	10	50.00	47	39	52.59
48	36	36.27	48	65	38.33	48	94	40.50	48	23	42.75	48	52	45.08	48	81	47.50	48	10	50.00	48	39	52.59
49	36	36.29	49	65	38.33	49	94	40.50	49	24	42.83	49	53	45.17	49	82	47.59	49	11	50.09	49	40	52.68
50	37	36.31	50	66	38.40	50	95	40.58	50	24	42.83	50	53	45.17	50	82	47.59	50	11	50.09	50	40	52.68
51	37	36.34	51	66	38.40	51	95	40.58	51	25	42.91	51	54	45.25	51	83	47.67	51	12	50.18	51	41	52.77
52	38	36.38	52	67	38.48	52	96	40.65	52	25	42.91	52	54	45.25	52	83	47.67	52	12	50.18	52	41	52.77
53	38	36.41	53	67	38.48	53	96	40.65	53	26	42.99	53	55	45.33	53	84	47.76	53	13	50.27	53	42	52.86
54	39	36.45	54	68	38.55	54	97	40.73	54	26	42.99	54	55	45.33	54	84	47.76	54	13	50.27	54	42	52.86
55	39	36.48	55	68	38.55	55	97	40.73	55	26	42.99	55	56	45.41	55	85	47.84	55	14	50.35	55	43	52.95
56	40	36.52	56	69	38.63	56	98	40.81	56	27	43.07	56	56	45.41	56	85	47.84	56	14	50.35	56	43	52.95
57	40	36.55	57	69	38.63	57	98	40.81	57	27	43.07	57	57	45.50	57	86	47.93	57	15	50.44	57	44	53.04
58	41	36.59	58	70	38.70	58	99	40.88	58	28	43.15	58	57	45.50	58	86	47.93	58	15	50.44	58	44	53.04
59	41	36.62	59	70	38.70	59	99	40.88	59	28	43.15	59	58	45.58	59	87	48.01	59	16	50.53	59	45	53.14

Table 3--Values of D^{-3} for values of D

D	D^{-3}									
	0	1	2	3	4	5	6	7	8	9
0.980	1.0625	1.0621	1.0618	1.0615	1.0612	1.0609	1.0606	1.0602	1.0599	1.0595
1	1.0592	1.0589	1.0585	1.0583	1.0580	1.0576	1.0573	1.0570	1.0566	1.0563
2	1.0560	1.0556	1.0554	1.0551	1.0547	1.0544	1.0541	1.0537	1.0534	1.0531
3	1.0527	1.0524	1.0522	1.0519	1.0515	1.0512	1.0509	1.0505	1.0502	1.0499
4	1.0495	1.0492	1.0490	1.0487	1.0483	1.0480	1.0477	1.0473	1.0470	1.0467
5	1.0464	1.0460	1.0457	1.0455	1.0452	1.0448	1.0445	1.0442	1.0438	1.0435
6	1.0432	1.0429	1.0425	1.0422	1.0419	1.0417	1.0413	1.0410	1.0407	1.0404
7	1.0400	1.0397	1.0394	1.0391	1.0387	1.0384	1.0381	1.0378	1.0376	1.0372
8	1.0369	1.0366	1.0363	1.0359	1.0356	1.0353	1.0350	1.0347	1.0343	1.0340
9	1.0337	1.0334	1.0332	1.0328	1.0325	1.0322	1.0319	1.0316	1.0312	1.0309
0.990	1.0306	1.0303	1.0300	1.0297	1.0293	1.0290	1.0287	1.0284	1.0281	1.0279
1	1.0275	1.0272	1.0269	1.0266	1.0263	1.0260	1.0256	1.0253	1.0250	1.0247
2	1.0244	1.0241	1.0238	1.0234	1.0231	1.0228	1.0225	1.0222	1.0219	1.0216
3	1.0213	1.0210	1.0207	1.0204	1.0201	1.0198	1.0195	1.0192	1.0188	1.0185
4	1.0182	1.0179	1.0176	1.0173	1.0170	1.0167	1.0164	1.0161	1.0157	1.0154
5	1.0151	1.0148	1.0145	1.0142	1.0139	1.0136	1.0133	1.0130	1.0127	1.0124
6	1.0121	1.0118	1.0115	1.0112	1.0109	1.0106	1.0103	1.0100	1.0097	1.0094
7	1.0091	1.0088	1.0085	1.0082	1.0079	1.0076	1.0073	1.0069	1.0066	1.0063
8	1.0060	1.0057	1.0054	1.0051	1.0048	1.0045	1.0042	1.0039	1.0036	1.0033
9	1.0030	1.0027	1.0024	1.0021	1.0018	1.0015	1.0012	1.0009	1.0006	1.0003
1.000	1.0000	0.9997	0.9994	0.9991	0.9988	0.9985	0.9982	0.9979	0.9976	0.9973
1	0.9970	0.9967	0.9964	0.9961	0.9958	0.9955	0.9952	0.9949	0.9946	0.9943
2	0.9940	0.9937	0.9934	0.9931	0.9929	0.9926	0.9923	0.9920	0.9917	0.9914
3	0.9911	0.9908	0.9905	0.9902	0.9899	0.9896	0.9893	0.9890	0.9887	0.9884
4	0.9881	0.9878	0.9875	0.9872	0.9869	0.9866	0.9863	0.9860	0.9857	0.9854
5	0.9851	0.9848	0.9845	0.9843	0.9840	0.9837	0.9834	0.9831	0.9828	0.9825
6	0.9822	0.9819	0.9816	0.9814	0.9811	0.9808	0.9805	0.9802	0.9799	0.9796
7	0.9793	0.9790	0.9787	0.9784	0.9781	0.9778	0.9775	0.9772	0.9769	0.9767
8	0.9764	0.9761	0.9758	0.9755	0.9752	0.9749	0.9747	0.9744	0.9741	0.9738
9	0.9735	0.9732	0.9729	0.9726	0.9723	0.9720	0.9717	0.9714	0.9712	0.9709
1.010	0.9706	0.9703	0.9700	0.9697	0.9695	0.9692	0.9689	0.9686	0.9682	0.9680
1	0.9677	0.9674	0.9671	0.9668	0.9666	0.9663	0.9660	0.9657	0.9654	0.9652
2	0.9649	0.9646	0.9643	0.9639	0.9637	0.9634	0.9631	0.9628	0.9626	0.9623
3	0.9620	0.9617	0.9614	0.9612	0.9609	0.9606	0.9602	0.9600	0.9597	0.9594
4	0.9591	0.9589	0.9586	0.9583	0.9580	0.9578	0.9575	0.9571	0.9568	0.9566
5	0.9563	0.9560	0.9557	0.9555	0.9552	0.9549	0.9547	0.9544	0.9540	0.9537
6	0.9535	0.9532	0.9529	0.9527	0.9524	0.9521	0.9518	0.9516	0.9512	0.9509
7	0.9507	0.9504	0.9501	0.9498	0.9496	0.9493	0.9490	0.9488	0.9484	0.9481
8	0.9479	0.9476	0.9473	0.9471	0.9468	0.9465	0.9463	0.9459	0.9456	0.9454
9	0.9451	0.9448	0.9446	0.9443	0.9440	0.9438	0.9434	0.9431	0.9429	0.9426
1.020	0.9423	0.9421	0.9418	0.9415	0.9412	0.9409	0.9406	0.9404	0.9401	0.9398

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PRECIPITATION AT BARROW, ALASKA, GREATER THAN RECORDED

Robert F. Black

(Publication authorized by the Director, U. S. Geological Survey)

Abstract--During the winter of 1949-1950 data on depth and density of snow on the ground near Barrow, Alaska, revealed two to four times as much water equivalent as was recorded with the standard eight-inch precipitation gage of the U. S. Weather Bureau. Indirect evidence on summer precipitation supports the conclusion that precipitation is greater than recorded. Wind effects are believed to be responsible for the difference in water equivalents and for an annual efficiency of the gage of 25 to 50 pct. Total precipitation thus may be more than 16 inches instead of about four inches as recorded. Other Arctic stations in windy areas doubtless are similarly affected.

Over a 31-year period at Barrow, Alaska, the mean annual precipitation, as recorded by the U. S. Weather Bureau with a standard eight-inch precipitation gage, is 4.23 inches, of which about half is snow. During the summers of 1946, 1947, and 1950 and the winter of 1949-1950 at the Arctic Research Laboratory four miles northeast of Barrow, while on a permafrost research project sponsored jointly by the U. S. Geological Survey and the Office of Naval Research, the writer obtained data that indicate that actual precipitation is two to four times as great as that recorded. This approximates in magnitude the error of 32 pct found by HELMERS [1952, pp. 67-68] in Idaho. The difficulties of measuring actual precipitation in windy areas are well known and are not discussed; experiments for shielding of gages have been going on for 100 years [WARNICK, 1953]. In an attempt to evaluate records of precipitation at Barrow, the writer presents two indirect methods which require measurements of snow on the ground and of the frequency and degree of saturation of the active layer over permafrost.

From October 1, 1949, to June 10, 1950, the Weather Bureau in its mimeographed monthly summary of Barrow data, recorded a total snowfall of 19.9 inches (Fig. 1) with a water equivalent of 2.20 inches. Of the 253 days only 36 days were without snowfall; only 1.4 inches of snow fell on days with maximum wind (Civil Aeronautics Authority records) less than 15 mi/hr (Fig. 1). The Weather Bureau also reported an average maximum depth of snow on the ground near the station during May 6-12, 1950, of 23 inches (see Fig. 1 for complete profile). Six snow-depth profiles by the writer, of localities two to four miles northeast of the weather station, are shown on Figure 1; and the average maximum depth is superimposed on the Weather Bureau profile. The maximum average depth of snow for the tundra as a whole two to four miles northeast of Barrow was estimated to be about 16 inches; the depth decreased northward to about ten inches at the coast. The depth inland from Barrow is reported to be greater than at Barrow, but the writer has no factual data.

The differences in depth of snow on the ground are attributed largely to wind drifting. Barrow is on the Arctic Ocean ten miles southwest of Point Barrow, the northermost point of land in Alaska, and five miles southwest of the apex of the mainland; Elson Lagoon lies five miles to the northeast and east. The land surface is less than 100 ft above sea level for tens of miles and presents little obstruction to wind. The mean hourly wind speed over a period of 24 years, as recorded by the Weather Bureau is 12.1 mi/hr. Perhaps because of local turbulence in town the velocities recorded by the Weather Bureau are less than those recorded by the Civil Aeronautics Authority with its newer equipment four miles to the northeast (see Table 1). According to data of the Civil Aeronautics Authority winter winds of 1949-1950 of velocities of 15 mi/hr or more occurred on 199 of 240 days (Table 1) and, as can be seen in Figure 1, winds blew almost exclusively from the ocean. Velocities were higher in early winter than in late winter. Shore-fast ice takes several months to cover an appreciable area, so that its snow cover can drift into Barrow as fast as the local snow drifts out. Thus an unknown but appreciable amount of snow in early winter especially falls in the area but is lost by wind drift out to sea or inland; snow is very rarely replenished at Barrow by southerly winds. Growth of hoar on the surface of the snow partly balances sublimation, but their quantitative effects are not known to the writer and are disregarded. Relative humidity during the winter of 1949-1950 (Table 2) suggests that sublimation is more important than condensation as was found under somewhat similar conditions in Greenland by CHURCH [1941, pp. 29-45]. If so, the error would be larger. No

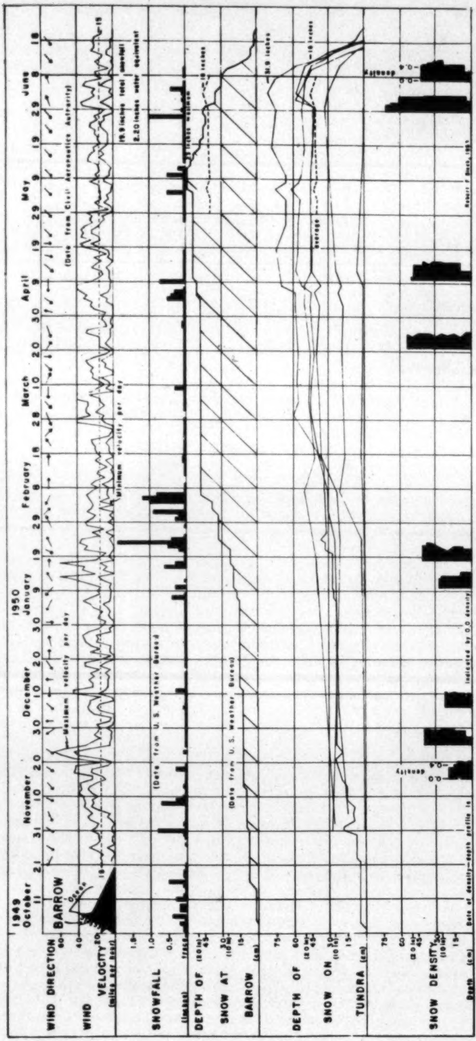

Fig. 1--Some climatic data for Barrow, Alaska

Table 1--Comparison of wind velocities recorded by the U.S. Weather Bureau and Civil Aeronautics Authority from October 22, 1949, to June 18, 1950; 240 days

Wind velocity	Number of days	
	U. S. Weather Bureau	Civil Aeronautics Authority
mi/hr		
Less than 15	78	41
15 or more	162	199
25 or more	47	100
35 or more	10	32
45 or more	0	10

Table 2--Mean monthly relative humidity October, 1949, through May, 1950[a]

Month	Relative humidity			
	02h 30m	08h 30m	14h 30m	20h 30m
	pct	pct	pct	pct
Oct., 1949	88	87	88	86
Nov., 1949	74	71	72	72
Dec., 1949	67	68	67	68
Jan., 1950	72	72	70	73
Feb., 1950	67	66	65	63
Mar., 1950	63	64	61	63
Apr., 1950	71	72	73	73
May, 1950	87	88	55	87

[a] Data of U. S. Weather Bureau, Local Climatological Summary for Barrow, Alaska, 1949 and 1950.

doubt these effects can be evaluated by an analysis of all data being collected by the U. S. Weather Bureau, but it is beyond the scope of this paper.

During the winter, 112 snow densities were determined with a National Research Council of Canada snow kit [KLEIN, 1949, pp. 109-117; KLEIN, PEARCE, and GOLD, 1950], with straight-walled test tubes about 12 mm in internal diameter and with square plastic boxes about 18 cm on a side. Each device was checked against the other in uniform snow; the test tubes were determined as most suitable, and most readings were made with them. Samples were collected horizontally in the walls of pits and were spaced at vertical intervals of five cm or less, depending on variations within the snow. Representative profiles are shown at the bottom of Figure 1. The average density of the snow was about 0.40.

Using the maximum average snow depth of 10, 16, 18, and 23 inches on the ground and the density of 0.4, the water equivalents are respectively 4.0, 6.4, 7.2, and 9.2 inches. Thus the snow on the ground, which because of wind drifting and possibly sublimation represented a minimum, still was two to four times as much as that caught by the standard precipitation gage. The highest value is considered more representative of the tundra inland from the coast.

Higher average wind velocities are recorded by the Weather Bureau during summer than during winter, and summer precipitation is commonly in the form of mist, drizzle, or very light rain. Several indirect lines of evidence support the belief that the efficiency of the standard precipitation gage is almost as low in summer as in winter. For example, spring breakup occurs precipitously about early to middle June and the snow melt runs off prior to the thawing of the ground. By mid-July much of the active layer has thawed and dried out. During the period from mid-July to freeze-up in latter September and early October the active layer is repeatedly saturated during rainy periods and is partly dried afterwards. The active layer averages 8 to 15 inches in thickness; the maximum range is about 6 to 40 inches. It is composed of well-rounded grains of fine sand and silt predominantly, although fine gravel, clay, and organic matter locally constitute large proportions of the total. From moisture-content determinations of frozen, saturated ground it is estimated that pore space is 20 to 40 pct. Thus the active layer on the average can contain between

1.6 and 6.0 inches of precipitation before it is saturated; three inches is about average. It is estimated that during the summers of 1946, 1947, and 1950 about six to nine inches of summer rain was needed to saturate the soil to the extent and as many times as were witnessed. These amounts are three to four times the recorded summer rainfall.

Perhaps 50 to 75 pct of the land is covered with lakes and small ponds with most overflow outlets running all summer. Streams are integrated over most of the surface, and flow throughout the summer. Even though permafrost prevents underground drainage and all runoff is on the surface, surely these would be dry if only two inches of precipitation fell during the summer; the strong winds and luxuriant vegetation by evaporation and transpiration alone would use more than two inches.

Another very crude check was obtained during the period August 18-20, 1946. The station at Barrow reported 0.88 inch of precipitation during moderate to strong winds while during the same period a flat-bottom boat with ten-inch straight sides and about 35 sq ft of area, on shore and out of reach of spray, accumulated more than three inches of water.

In conclusion it has been shown that snow on the ground is at least two to four times that caught in the standard precipitation gage at Barrow, Alaska. Indirect evidence suggests that the average efficiency of the gage for rain and snow is about 25 to 50 pct, because of wind effects. Thus the actual precipitation at Barrow is greater than recorded and may be two to four times as great. No doubt other stations in windy areas in the Arctic will show similar differences. If these findings can be substantiated in other ways, our present thinking of the "arid" Arctic must be changed. In studies of climatology, glaciology, geomorphology, water supply, permafrost, ecology, and other natural sciences the implications are obvious.

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DISCUSSION

Walter T. Wilson (U. S. Weather Bureau, Washington 25, D. C.)--As a by-product of his studies of permafrost, Black has presented convincing evidence that considerably more precipitation occurs in arctic regions than gage catch indicates. The reasonableness of his conclusion is displayed in Figure 2 which shows the results of his and others' investigations of the relation of gage catch to wind speed. Only enough data have been plotted to suggest the general trend. Many more data can be found by reference to KURTYKA's [1953] bibliography. Black's points in this figure plot at the fringe of the general relationship. While he cites considerable latitude in the magnitude of his estimate, it might also be noted that the natural exposure conditions at Barrow are unusually severe.

If there were some simple way to reduce the scatter in this figure, it would be possible to correct gage-catch records objectively on the basis of station windiness. However, the scatter results in part from variation in the size of the falling particles, differences in anemometer height and exposure, and other influences that are not convenient parameters. Black's discussion of the two anemometers at Barrow shows a variation in wind which is commonplace over smaller distances than the four-mile span at Barrow. While the mean windiness of a site is a good measure of its suitability for measuring precipitation, a refined definition of the relationship would require wind direction as well as speed, and the vector would have to be integrated over periods during which precipitation actually occurs instead of including fair-weather wind in the average.

In many areas where snow accumulates, the weather observers are instructed to augment the gage data, when their judgment recommends it, with data from snow on the ground. The accumulation of snow on the ground usually exceeds what enters a gage, because the gage obstructs the air

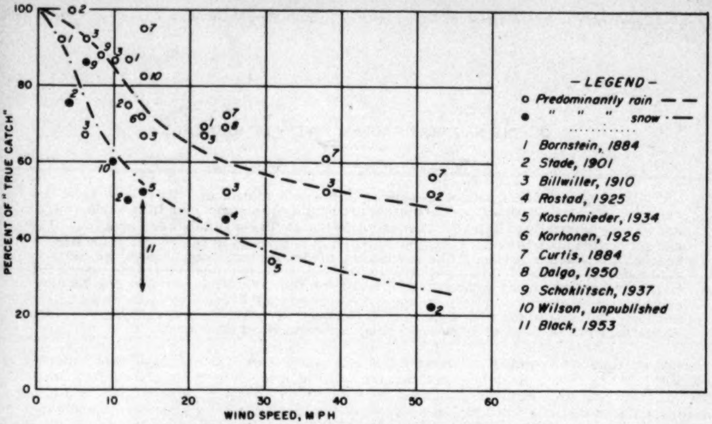

Fig. 2--General relation of precipitation catch to wind speed

movement, and the vertical component of the air trajectory immediately above the gage may be very large with respect to the settling speed of the snow particles. Moreover, the drifting of snow and the selection of a representative point at which to measure the snow are problems only partly solved. For measurements of daily fall the observer usually takes his sample from a standard site shown by experience to have a minimum of bias due to drifting. For daily measurements of water equivalent of the entire snowpack, the removal of successive cores for melting or weighing necessitates a changed location from day to day. The result is a confounding of the variation of water equivalent from day to day with its variation from place to place. It is known that snow density varies less over an area than either the snow depth or its water equivalent. Accordingly, the observer eliminates much of the areal variability by measuring density at new places from day to day and by measuring the depth concurrently at a nearby but unvarying location. A permanently fixed stake is commonly used for observing snow depth. The water equivalent for the station is computed by multiplying the depth at the fixed point by the density observed nearby. Black used this technique as part of the basis for his estimate of seasonal accumulation.

With the living conditions as they naturally are at Barrow, and with the required emphasis by the small staff there on the taking of upper-air soundings and other data for forecasting, it can be understood why these refinements in observing precipitation are seldom made. Black suggests the increasing importance of precipitation data in the Arctic. This trend may eventually bring the economic support which would be necessary for much expansion and improvement of the observations of water resources there. In the meantime, Federal bureaus can allocate only limited effort in that direction.

Means of improving the representativeness of precipitation measurements in Alaska are currently under review. Among them are shielded gages with improved mechanism for cold-weather performance. Even the best shields overcome only part of the deficiency of an inherently poor exposure, and a larger scale of sheltering is sometimes necessary. The cost of building and maintaining a large artificial shelter at a station like Barrow would be extremely high. The use of existing buildings for their shelter is questionable because of lack of symmetry, and the danger of over-catch cannot be overlooked. The possibility of establishing natural shelter there by growing a grove of conifers may not be too remote. While the northern limit of natural tree growth is many miles from Barrow there are indications that this limit is determined by natural modes of propagation rather than by the severe climate and soil conditions.

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ON THE NATURAL RADIOACTIVITY OF RAINFALL

Paul E. Damon and P. K. Kuroda

Abstract--Measurements by the authors of the natural radioactivity of rain water are reported. The radioactivity varied from one to 60 millimicrocuries per liter of rain water and was due primarily to RaB+C. The activities due to ThB and RaD were less than 10^{-10} and 10^{-11} curie per liter each, respectively. RaA is present in rain water at the time it reaches the Earth's surface. The mechanism for the accumulation of decay products in rain water is discussed. The total activity (per unit area and time) increases toward the limiting value determined by the supply of RaA from Rn. An average atmospheric Rn concentration within the cloud system of approximately 0.2×10^{-13} curie per liter is sufficient to supply the rain water with the observed radioactivity. The natural radioactivity of the atmosphere can be used as a tracer to study meteorological phenomena.

Introduction--The natural radioactivity of rain water (see Table 1) was first reported by WILSON [1902ab; 1903]. He determined that the half life of the activity was 30 minutes (RaB+C) and that there was little difference between the activity of rain water and snow. By 1913 it had been established that radon and thoron emanations are present in the atmosphere as indicated by Table 1, though BUMSTEAD [1904] had identified these in the atmosphere much earlier; the decay products are captured by cloud droplets and brought to the surface by atmospheric precipitation, and the activity of newly-fallen rain consists predominately of the radiations of RaB+C. According to PRIEBSCH [1932], the RaB+C activity of atmospheric precipitates can be explained by assuming that initially the atoms of the A-products are deposited on the drops.

Recently there has been a renewed interest in the radioactivity of rain water. This renewed interest has been brought about primarily by the necessity to monitor the contamination of the atmosphere caused by nuclear explosions. Presumably, considerable work is underway, but has not yet been published. Because of the sudden shift of interest from natural to artificial radioactivity, there is, perhaps, some confusion concerning the relative concentrations of the different isotopes in rain water (see Table 2).

Recent measurements of both radon and its decay products were made by one of the authors, P. K. Kuroda (unpublished), near Hot Springs, Arkansas. Using a dithizone extraction method, he found, as expected, a large excess of the decay products (6×10^{-9} curie per liter) and a deficiency (less than 4×10^{-11} curie per liter) of radon. The authors have found the short-lived decay-product activity of torrential rainfall to be as low as one millimicrocurie per liter (mmc/ℓ). The radioactivity of light rainfall has been invariably, considerably higher. RaD and fission products are also being studied. However, this paper is primarily concerned with the short-lived A-B-C decay products and the mechanism through which they are accumulated in rain water.

Meteorological data--The measurements, listed in Table 3, were made on rain water which resulted from the cooling of tropical marine air masses. The first low and the second low of the cyclonic wave train passed over northwest Arkansas on the days during which the measurements were made. The rainfall lasted about the same length of time in each case, but the second rainfall totaled only 0.08 inch (2 mm), whereas 0.82 inch (21 mm) fell during the first rainfall.

Experimental methods--Water samples were collected in glass or porcelain containers with collecting surfaces of 46 to 93 in^2 (300 to 600 cm^2). The water was transferred by a pipette to planchettes, evaporated, and counted either with a 2.9-mg/cm^2 end-window Geiger counter, with a loop-line windowless Geiger tube [DAMON, 1951] or with a Lauritsen electroscope with a 0.003-mm aluminum window [KURODA and YOKOYAMA, 1948c]. The instruments were calibrated with known amounts of RaB+C from radium standards of the U. S. Bureau of Standards. One cm^3 of rain water has sufficient activity to be counted with an end-window Geiger tube.

The activities of RaB+C and rates of precipitation are given in Table 3. The decay of activity measured by end-window and windowless counters is given in Figure 1. The activities of ThB and RaD were less than 10^{-10} and 10^{-11} curie per liter each, respectively. The activity above 10^{-10} curie per liter can be ascribed to the disintegration of RaB+C alone (for the data in Table 3).

Table 1--Literature review of radioactivity of rain water and snow

Date	Locality	Radioactivity	Investigator
1902	Cambridge and Peebles, England	190 ml of rain water produced an activity 100 times greater than the instrument background. (half life = about 30 minutes)	WILSON [1902]
1903	Peebles, England	50 ml sample, 3.6 d/m (background is 0.19 d/m. There is no indication of any difference in the intensity of the radioactivity obtained from equal weights of snow and rain water.	WILSON [1903]
1905		$KAl(SO_4)_2$ was added to one liter of rain water and precipitated with NH_4OH. During the rainfall, the radioactivity decreases. Fresh snow was found to be three to five times more active.	JAUFMANN [1905]
1906 Mar. to May		Newly fallen rain was always found to be radioactive. In about two hours the activity of the rain samples disappeared. Within 30 minutes after the beginning of rainfall, a very pronounced decrease in the activity of the rain took place. The activity of newly-fallen rain is particularly noticeable during a thunderstorm especially when accompanied by hail.	COSTANZO and NEGRO [1906]
1908		Fresh rain water contains RaB and RaC. The activity varied from 0.2 to 3.0 millimicrocuries per liter.	GOCKEL and WULF [1908]
1913 Jan. 16	Madrid, Spain	Rain water contained a considerable amount of emanation which decayed at a rate following the Curie formula. Activity could not be detected in rain water which had been sealed in a bottle for 12 days.	CASTILLO and FERNANDEZ [1913]
1932	Austria	The radioactivity of the atmospheric precipitates (rain and snow) was determined in Graz, in Lans (Tyrol) and in Innsbruck in 33 cases. The decay curves of the activity show the presence of radium and sometimes also of thorium products. From the activity of the radium products (RaA, RaB, RaC) in each case the equivalent amount N of radium emanation as mother substance was calculated. It was found that this quantity N is in various cases proportional to the amount M of rain or snow-water within wide limits. It is tried to explain this theoretically, to define a “specific activity” N/M accordingly and to calculate this in each case. Thus a specific activity of the order of 50 Eman (10^{-10} curie pro litre) was found with samples of rain after “föhn” wind in Tyrol. The equivalent amount N as calculated from the observations of the radioactive deposits is in accordance with the known emanation content of the air as obtained from direct observations. It may be stated that the radioactivity of the atmospheric precipitates can be explained by assuming that mainly the atoms of the A-products are primarily deposited on the drops.	PRIEBSCH [1932]
1947	Masutomi, Japan	Date Radioactivity of the decay products (mmc/ℓ)	KURODA and YOKOYAMA [1948ab]
		June 15 30.0	
		June 15 34.0	
		Aug. 17 19.0	
		Aug. 17 15.0	
		Aug. 17 18.0	
	Tokyo, Japan	Aug. 27 5.0	
		Aug. 27 6.5	
		Aug. 30 25.0	
		Sep. 2 15.0	
		Oct. 6 9.0	
		Nov. 20 8.0	

(Continued)

Table 1--Literature review of radioactivity of rain water and snow (concluded)

Date	Locality	Radioactivity	Investigator
1950		Determination of the radioactivity of 33 samples of atmospheric precipitates (snow and rain) showed that snow usually has a greater activity than rain, that rain in thunderstorms is more active than ordinary rain and that at least a certain amount of activity is acquired during fall from clouds to ground level. Decay products of thoron were also found in precipitates.	STEFANIZZI [1950]
1952	United States	The concentrations of the various radioactive decay products of radium in the air have been determined by observing the beta activity of pieces of filter paper through which air has been passed, and of chemically separated isotopes obtained from such filter papers. The relative amounts of long-lived and short-lived products found indicate that besides the radioactive decay of the substances, some other process which removes radioactive particles from the air is active. The mean life of the particles with respect to this other removing process is found to be about 10 days. The hypothesis that this process is the capture of the radioactive particles by rain droplets (clouds) is consistent with measurements made of the radioactive content of rain water. On the other hand, the removal of the ionized radioactive particles by electric field of the Earth leads to a much smaller effect.	BLIFFORD, LOCKHART, and ROSENSTOCK [1952]

Table 2--Radioactive isotopes in rain water

Radioactive isotope	Specific activity	Investigator and remarks
	curies/liter	
Rn	10^{-11}	Authors
RaB + C	10^{-9} to 10^{-7}	Authors
RaD	10^{-13} to 10^{-12}	Authors, and BLIFFORD, LOCKHART, and ROSENSTOCK [1952]
Ra	10^{-12}	Authors (only one determination)
ThB	10^{-13} to 10^{-10}	Authors
Tritium	10^{-11} to 10^{-12}	Libby (private communication)
Fission products	10^{-12} to 10^{-9}	Authors, June 5 to Sep. 4, 1953

Theory and results--The distribution of the decay products of radon and thoron in the atmosphere has been studied by WILKENING [1952] who ionized atmospheric particles, separated the resulting ions according to mobility, and deposited them on a collecting surface which was then inserted in a methane proportional counter to determine the activity. He found that most of the decay products were attached to particles having diameters in the range of 0.001 to 0.04 micron. The collision properties of the decay products are such that the decay products rapidly attach to particulate matter suspended in air. The initial charge on the RaA nucleus may assist in the process of attachment, because it is known that the conductivity of the atmosphere is very low when the air is dusty or when condensation takes place. Under these conditions the fast or molecular ions become attached to the more massive ions with slower velocity [HUMPHREYS, 1940]. At any rate, it is apparent that under these conditions the decay products will attach themselves to cloud droplets and condensation nuclei in the atmosphere, and a large fraction of them or their short-lived descendants will be readily available for transport to the ground when precipitation begins. BLIFFORD, LOCKHART, and ROSENSTOCK [1952], who have studied the relative amounts of long- and short-lived products of radon in air, conclude that the primary process of removal of the radioactive decay products is capture by rain droplets.

Table 3--Radioactivity of rainfall recorded at Fayetteville, Arkansas

Date	Interval of collection	Rate of precipitation ℓ/m^2 min	RaB, C activity	
			Counter method	Lauritsen method
		(0.0394 in^3/ft^2 min)	curie × 10^9	curie × 10^9
Dec. 19, 1952	12h 36m - 12h 50m	0.013	....	33
	12h 58m - 13h 08m	0.090	....	21
	13h 08m - 13h 18m	0.090	....	22
	13h 19m - 13h 31m	0.050	....	22
	13h 31m - 13h 41m	0.030	....	29
	13h 40m - 13h 50m	0.015	41	....
	13h 41m - 13h 51m	0.015	....	41
	13h 52m - 14h 02m	0.015	....	39
	14h 02m - 14h 12m	0.009	....	33
	14h 12m - 14h 22m	0.029	....	41
	14h 22m - 14h 32m	0.012	....	33
	15h 27m - 15h 35m	0.009	50	....
Dec. 20, 1952	20h 59m - 21h 01m	0.003	....	59
	21h 00m - 21h 10m	0.003	58	....
	21h 43m - 21h 53m	0.006	26	....
	21h 44m - 21h 45m	0.006	....	25
	22h 20m - 22h 30m	0.006	31	....
	23h 49m - 23h 50m	0.005	....	28

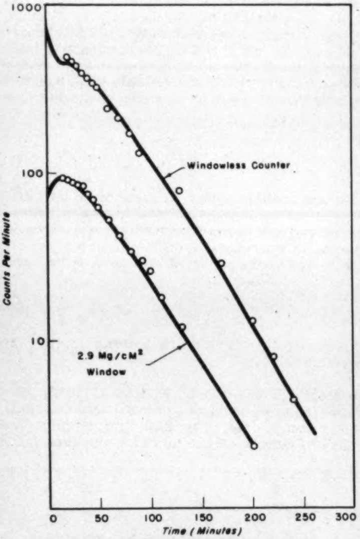


Fig. 1--Relationship of decay of activity to time after sampling of rainfall

There are several causes of colloidal instability within clouds; however, according to Bergeron [PETTERSON, 1940], the all-important cause is the co-existence of water droplets and ice in the cloud. Under this condition, the vapor pressure would be a compromise between the two saturation vapor pressures, with the result that the water droplets evaporate and condense on ice particles. The ice particles finally become too heavy and fall through the cloud, colliding with water droplets and growing until they leave the cloud. The mechanism is continued throughout the duration of the storm by the cooling of the air mass. Condensation droplets are formed, ice particles grow, fall, and sweep out cloud droplets which are replaced by growing condensation droplets.

Radon is present throughout the atmosphere in small quantities (Table 4) and continually supplies decay products which attach to aerosols and condensation droplets. As equilibrium between radon and RaA + B + C is established in about four hours, any cubic meter of air should be essentially in equilibrium with these short-lived decay products unless some disturbing force such as precipitation upsets this equilibrium. In this case the decay products are swept downward by the growing rain drops. Initially, equal activities of the decay products will be present, but if the rainfall continues with sufficient intensity, the atmospheric radioactivity will be essentially limited to the gas radon and the short-lived decay product RaA (3.05 min) supplied directly by radon. Although the amount of radon in the atmosphere is affected by

Table 4--Radon content of the atmosphere

Place	Altitude	Radioactivity	Investigator
		curie/$\ell \times 10^{13}$	
Pacific Ocean	Sea level	0.0033	BAUER and SWANN [1916]
Sub-Antarctic	Sea level	0.0004	
Land (average)	Ground level	0.088	
Land (average)	Ground level	1.30	HESS [1928]
	1000 m	Theoretical value for average state of mixing or eddy diffusion is 0.23	
Land (average)	Ground level	1.3	MESSERSCHMIDT [1933]; EVANS and Others [1938]
Free air over land (average)	5000 - 6000 m	0.31	GARRIGUE [1950]
	6000 - 7000 m	0.34	
	7000 - 8000 m	0.22	
	8000 - 9000 m	0.20	
Summit of Puy de Dome Mountain	1500 m	0.10 - 20.0	GARRIGUE [1950]

meteorological conditions [ALIVERTI and LOVERA, 1949; MESSERSCHMIDT, 1933], its long half life and low concentration in rain water prevent a rapid depletion during the course of a storm. For instance, assuming the supply of radon from the Earth's surface to be cut off completely and a radon concentration in rain water equal to the upper limit found at Hot Springs (4×10^{-11} curie per liter), the depletion of radon during a 24-hour, one-inch (2.54 cm) rain would only be about ten per cent of the radon present in a 16,400-ft (5000 m) atmospheric column. The particularly high activity of rainfall upon sudden initiation of rainfall in a thunderstorm and noticeable decrease after the rainfall continues for a short time [see Table 1; CONSTANZO and NEGRO, 1906; STEFANIZZI, 1950] can possibly be explained by depletion of the longer lived decay products (RaB+C).

These ideas can be put in mathematical form

$$A_t = A_sR = (T, R, S,) \quad \ldots\ldots\ldots\ldots \quad (1)$$

That is, the total activity per unit area and time is a function of time T, rate of rainfall R, and supply of radioactive nuclides S which is also equal to the activity per unit volume of rain water A_s times the rate of rain fall. As a first approximation, if we consider the parent source not to be depleted with time, it is reasonable to assume an exponential growth of total activity with increased rate of fall toward the limiting value determined by the supply of radium A from radon (Fig. 2)

$$A_t = A_sR = A_{max}\,(1 - e^{-\sigma R}) \quad \ldots\ldots\ldots\ldots \quad (2)$$

When $e^{-\sigma R}$ approaches zero, any additional rainfall serves only to dilute the activity A_s (Fig. 3); σ is an arbitrary constant which must be evaluated from the data.

Alternative and perhaps less arbitrary relationships can be derived. PRIEBSCH [1932] considered the accumulation of decay products on a rain drop to be analagous to their accumulation on a charged wire with the initial deposition of the A-products only. The feasibility, of the primary deposition of A-products only, can be seen by a study of Figure 4. If the following condition holds

$$K_2 \gtreqless K_1 > \lambda_a >> K_3 >> K_4 \quad \ldots\ldots\ldots\ldots \quad (3)$$

$$K_2 \propto R \text{ (rate of rainfall)}$$

Where $K_1, K_2, K_3, K_4, \lambda_a$ are rate constants defined by the diagram; then the radioactivity of rain water can be explained by primary deposition of A-products only. Thus, when this condition holds, the A-products exist as free ions for a very short time until they become attached to either

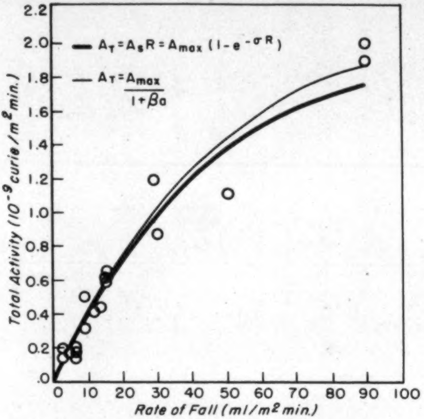


Fig. 2--Relationship of total RaB + C activity to rate of rainfall

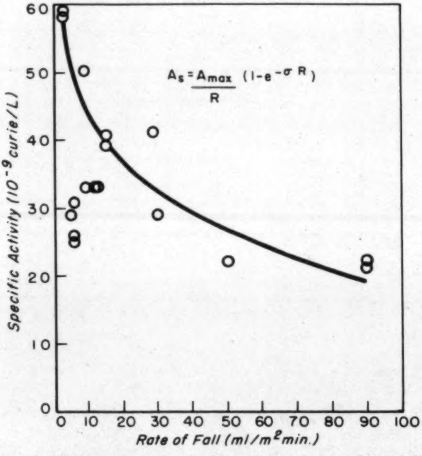
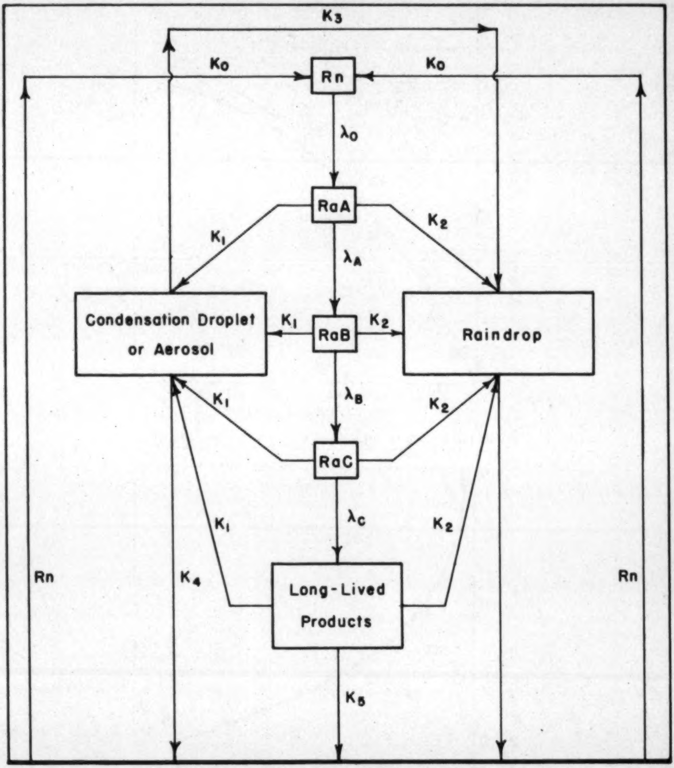


Fig. 3--Relationship of specific activity of rate of rainfall

a condensation droplet or a rain drop. If RaA attaches to a condensation droplet, the Ra(B+C) products are formed and, according to this hypothetical condition, largely decay to RaD before the condensation droplet becomes unstable or is swept out by collision with a rain drop. BLIFFORD, LOCKHART, and ROSENSTOCK [1952] have studied the long-lived decay products and they conclude that these decay products are captured by condensation droplets and removed by rain rather than by the Earth's gravitational or electric field. That is, with reference to Figure 4, they conclude



K3
Ko
Rn
Ko
λo
RaA
K1
K2
λA
Condensation Droplet or Aerosol
K1
RaB
K2
Raindrop
K1
λB
K2
RaC
K1
λC
K2
Rn
K4
Long-Lived Products
Rn
K5

EARTH'S SURFACE

Fig. 4--Migration of radon and decay products in the atmosphere

$K_3 >> K_4$. If RaA attaches to a rain drop, it decays to RaB+C during the transit of the rain drop earthward. As the rate of rainfall increases, more of the RaA is swept out directly by raindrops.

Considering RaA alone, the equilibrium relationship, in the absence of areosols, condensation droplets or rain, is given by

$$N_a \lambda_a = N_o \lambda_o \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where N_a and N_o are the numbers of free RaA and radon nuclides respectively, and λ_a, λ_o are the respective radioactive decay constants. After rainfall has begun and continued for a sufficient length of time (< 10 min), a new equilibrium in the atmosphere is reached

$$N_a (\lambda_a + K_1 + K_2) = N_o \lambda_o \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Solving for the rate of sweep out by rain drops

$$N_a K_2 = N_o \lambda_o/(1 + \beta_a) \quad \text{(6a)}$$

where $\beta_a = (\lambda_a + K_1)/K_2$ because the RaB+C activity of an atmospheric precipitate will be proportional to the sweep out rate, this equation may be rewritten as follows

$$A = A_{max}/(1 + \beta_a) \quad \text{(6b)}$$

Where A is the total RaB+C activity of water arriving at the Earth per unit area and time for a rainfall of a given rate, and A_{max} is the maximum RaB+C activity obtained when K_2 is much greater than K_1 (Fig. 4).

If we assume that the reciprocal of β_a varies linearly with the rate of rainfall (K_2 = constant times R and K_1 constant) and set $\beta_a = 1/2$ when R = 100 cm^3/m^2 min (0.567 in^3/ft^2 min), Eq. (6b) is in excellent agreement with the data (Fig. 2). This agreement is, of course, not conclusive but serves to illustrate the type of argument that can be used.

The variation of activity with time after the collection of a sample will depend upon the distance traveled by the average RaA nuclide on a droplet and the velocity of the droplet. If only the beta particles are counted, the following equation should give the variation of activity with time for the limiting case when $e^{-\sigma R} \longrightarrow \beta_a \longrightarrow 0$

$$A_\beta = N_b \lambda_b + N_c \lambda_c = N_a^o \left(0.612e^{-\lambda_b t} - 0.104e^{-\lambda_a t} - 0.508e^{-\lambda_c t}\right) \quad \text{(7)}$$

where A_β = beta activity, N_a, $N_b + N_c$ are the numbers of atoms present, the superscript o refers to the initial number of nuclides collected by the raindrop, and λ_a, λ_b, λ_c are the respective decay constants. If alpha as well as beta particles are counted, the relationship will be

$$A_{(\beta+\alpha)} = N_a \lambda_a + N_b \lambda_b + 2N_c \lambda_c = N_a^o \lambda_a \left(0.918e^{-\lambda_a t} + 1.096e^{-\lambda_b t} - 1.014e^{-\lambda_c t}\right) \quad \text{(8)}$$

The experimental values are plotted in Figure 1 along with the theoretical curves. Zero time is displaced by a five-minute interval to take some account of transit time. The theoretical and experimental values for the beta decay are in close agreement. Assuming a velocity of fall of four meters per second (13 ft per second) [HUMPHREYS, 1940] it would appear that the average point of collection for RaA nuclides is between 1000 and 2000 m (3300 and 6600 ft) altitude. However, a correspondingly more rapid decay was not always observed for lower rates of rainfall. This is to be expected when K_2 is appreciable and tends to substantiate the statement of STEFANIZZI [1950] that at least a certain amount of activity is acquired during the fall from cloud to ground level.

It is of interest to compute the amount of radon that must be present in the atmosphere to account for the radioactivity of the rainfall. For this purpose let us consider a section of the atmosphere 5000 m (16,400 ft) in height (typical height of cloud system) and one square meter (10.78 ft^2) in cross section from which the decay product RaA is extracted as fast as it is produced. From our measured value for total rainfall activity (2.0×10^{-9} curie/m^2 min) and (7) the initial RaA activity must have been about 20×10^{-9} curie/m^2 min and the number of RaA nuclides

$$N_a^o = A_T/\lambda_a \sim 3200 \text{ nuclides/m}^2 \text{ min} \quad \text{(9)}$$

The amount of RaA supplied will be the average activity of radon per liter in the column multiplied by the total volume of the collecting column.

$$N_a^o = A_{RN} \times \text{Vol} \quad \text{or} \quad A_{RN} = N_a^o/\text{Vol} \quad \text{(10)}$$

Because there are 1000 liters per cubic meter, the total volume in the 5000-m column is 5×10^6 liters and $A_{RN} \sim 6.4 \times 10^{-4}$ d/sec liter or about 0.2×10^{-13} curie of radon per liter, which is in reasonable agreement with directly measured values (Table 4).

Preliminary measurements in this laboratory on the radioactivity of snow indicate that there is no appreciable difference in the activity of snow and rain. This is not necessarily contradictory to earlier work as no allowance was made by previous investigators for the rate of precipitation.

It may be concluded, from this study of the short-lived products, that the average life time of a free ion during rainfall or condensation is short (less than one minute), and that a free ion can be directly captured by a falling rain drop as well as by condensation droplets. The capture process is quite efficient. A study now in progress of the longer-lived products may provide additional information concerning the condensation to rain-drop rate K_3.

The quantity of radioactivity should vary with the history and condition of the air mass, and the height and the structure of the cloud system within the collecting column. It is well known that the concentration of radon over the open oceans is less than over land (Table 4) and that the rate of escape of radon from the Earth is dependent upon such meteorological factors as temperature, sunlight, and barometric pressure [MESSERSCHMIDT, 1933; ALIVERTI and LOVÈRA, 1949].

The natural radioactivity of the atmosphere can be used as a tracer to study meteorological phenomena. The radioactivity measurement technique and instrumentation are quite simple but for a more extensive study considerable meteorological data are needed. The authors believe that if the study of the natural radioactivity of rainfall were carried on at meteorological laboratories, it would provide an interesting insight into meteorological phenomena.

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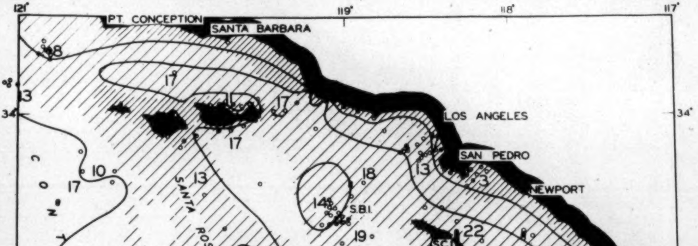
TRANSPARENCY OF WATER OFF SOUTHERN CALIFORNIA

K. O. Emery

(Contribution of Allan Hancock Foundation No. 126)

Abstract--Secchi disk readings off Southern California show a close relationship of water transparency to supply of detrital and, to a lesser extent, organic sediment along the mainland and island shores and to organic production in a large area of upwelling near the continental slope.

Introduction--Transparency is a useful and frequently measured property of sea water because it serves as a rough indicator of the amount of suspended material of either organic or inorganic origin. Among the various devices for measuring transparency, the Secchi disk is by far the simplest, though its precision is limited. Operation consists merely of measuring the depth at which a white disk of 30-cm diameter disappears from sight.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SANTA ROSA – CORTES RIDGE
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Fig. 1--Transparency of water off Southern California in terms of Secchi disk readings in meters; dots indicate positions of readings; numbers are mean values for groups of Secchi disk readings; S.C.I., Santa Catalina Island; S.B.I., Santa Barbara Island; T.B., Tanner Bank; and C.B., Cortes Bank; close cross-hatching, areas shallower than 100 m; wide cross-hatching areas 100-1000 m deep

During geological cruises in the period 1949 to 1953, 116 transparency readings were taken aboard Velero IV, the University of Southern California marine research ship. Routine measurements were made aboard ships of the Marine Life Program at Scripps Institution of Oceanography during 1949 to 1951. Paul L. Horrer kindly released to the writer 140 of these measurements that were taken off Southern California plus ten others from San Diego Bay. Robert Dill contributed two readings off San Diego. In studies of San Pedro Bay, J. L. BARNARD [1952] and Donn S. Gorsline of University of Southern California took 45 and 12 readings respectively. Thus, a total of 325 Secchi disk readings in the region is available. The positions of all except some of the closely spaced ones near Santa Barbara Island and San Pedro Bay are shown on Figure 1.

Variations--Although the Secchi disk readings are characterized by considerable local variation with time, mean values still present a regional pattern. Mean depths for groups of readings, indicated on Figure 1, were further grouped by contouring areas having 1 to 10, 11 to 15, and 16 to 25 m mean transparency. The spread of values at any given location is probably due largely to errors in measurement, but it partly also results from changes in sea state and to a minor extent from differences in time of day and degree of cloud cover when the readings were made.

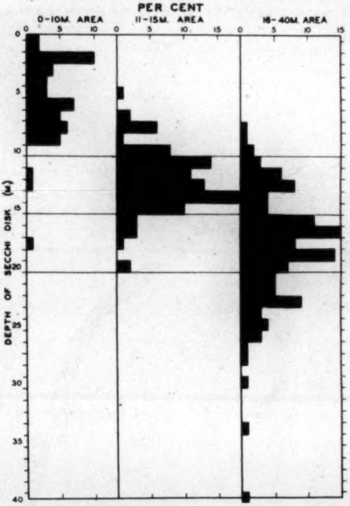

Fig. 2--Range of values for Secchi disk readings between the contours of Figure 1

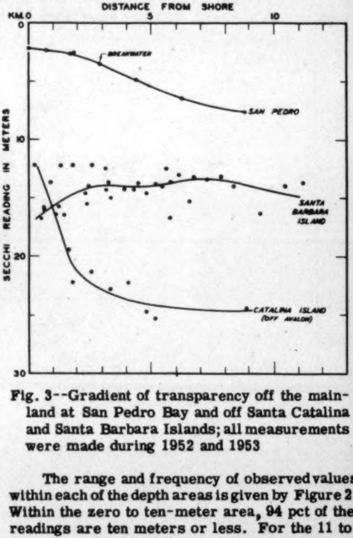

Fig. 3--Gradient of transparency off the mainland at San Pedro Bay and off Santa Catalina and Santa Barbara Islands; all measurements were made during 1952 and 1953

The range and frequency of observed values within each of the depth areas is given by Figure 2. Within the zero to ten-meter area, 94 pct of the readings are ten meters or less. For the 11 to 15-m area, 71 pct of the readings are between 11 and 15 m. Finally in the 16 to 25-m area, 69 pct are within that range. Only three readings exceed 28 m, one of which is 34 and another 40 m.

Significance of pattern--Very low transparencies of two or three meters occur near shore in San Pedro Bay with a gradual increase in a seaward direction (Fig. 3). Similar low transparencies exist in San Diego and Newport Bays, though little of the latter bay is deep enough for making Secchi disk readings. In all three bays the transparency is greater in the new sea water that enters at flood tide than at ebb tide after currents and waves have placed into suspension some of the sediment of the mud-flats. Plankton also contributes significantly to the turbidity. Readings of ten meters or less occur near shore along probably the entire coast owing to the presence of suspended inorganic sediment that is derived from wave erosion of sea cliffs and shallow sea floors and from the redistribution of stream-contributed sediments plus plankton and organic debris from seaweeds. Low transparencies near Tanner and Cortes Banks may result from wave stirring of sediment on the shallow bottom.

Intermediate transparency, 11 to 15 m, fringes the coastal belt of low transparency and also occurs around the islands, where it is probably a result of cliff erosion by waves. At Santa Barbara Island, where kelp beds provide some protection from waves, there is a suggestion of greater transparency near shore than farther out (Fig. 3). The main expanse of intermediate transparency, however, is a broad belt in the western half of Figure 1 that overlies the region between the continental slope and the Santa Rosa - Cortes Ridge. Several roughly parallel submarine ridges exist in this region, but, as little of the bottom is shallower than 100 m, it does not seem likely that wave stirring of bottom sediments has reduced the transparency. Evidently, the explanation is to be sought in the upwelling in this area that has been suggested on the basis of low water temperatures [SVERDRUP and FLEMING, 1941] and abundant diatom populations [SVERDRUP and ALLEN, 1939; SARGENT and WALKER, 1948] which owe their presence to upwelled nutrient salts.

The area of deepest mean transparency, 16 m or more, is in two main regions. One of these is over the abyssal sea floor west of the continental slope where it evidently forms the eastern portion of a large oceanic area of high transparency. The other region, continuous with the first one around the south end of the Santa Rosa - Cortes Ridge, forms the bulk of the eastern half of Figure 1. It is far east of the main area of upwelling and the original content of nutrient salts has largely been depleted by plankton, which in turn have mostly been utilized by grazing animals during the travels of the water after upwelling. Islands and banks here evidently produce little sediment, perhaps because of their somewhat sheltered position from the large storm waves that usually come from the northwest.

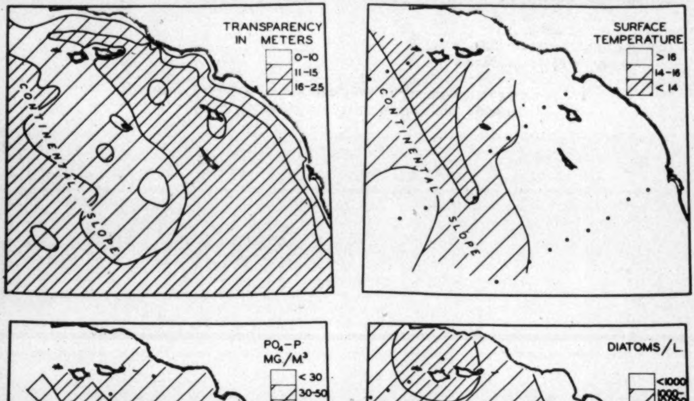

Fig. 4--Comparison of transparency, temperature, phosphate concentration, and diatom population: transparency from Fig. 1--1949 to 1953; temperature at surface in degrees Centigrade from *E. W. Scripps* Cruise III, June 7-16, 1938 [SVERDRUP and STAFF, 1942]; phosphate concentration at 50 m in mg/m^3 from *E. W. Scripps* Cruise XV, May 29-June 7, 1940 [SVERDRUP and STAFF, 1944]; diatom population at 70 m in cells per liter from *E. W. Scripps* Cruise III, June 7-16, 1938 [SVERDRUP and ALLEN, 1939]

The similarity of general patterns of transparency, surface water temperature, nutrient concentration, and diatom count is illustrated by Figure 4. Although all the data were not obtained simultaneously, or even during the same year, only minor differences between these four general patterns exist. Nevertheless, it should be remembered that the patterns are only generalizations, and that observations made at any particular time may depart more or less widely from them.

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BATHYMETRY OF THE PUERTO RICO TRENCH

John Northrop

(Hudson Laboratories, Contribution No. 2)

Abstract--The Puerto Rico Trench extends for about 400 mi in a generally east-west direction 80 mi north of Puerto Rico and has a five to ten-mile wide "flat" floor 4350 fm deep. The Trench is separated from the Nares Basin to the north by a 2900-fm divide, and is roughly paralleled to the south by a series of seamounts which form an interrupted ridge from 2700 to 3700 fm deep. South of this ridge are basins, 4000 to 4100 fm deep, which may drain into the Trench through San Juan Canyon. The Trench floor has two kinds of sediment in alternating layers up to several meters thick: (1) layers of abyssal red clay with low carbonate content, which is "normal" at this great depth, and (2) anomalous layers of highly calcareous sands showing excellent graded bedding and shallow water benthonic fossils. The layers of anomalous sand are attributed to the action of turbidity currents, which may have transported the sediment from neighboring island platforms down submarine canyons and deposited it in the Trench, rather than to former shallow water conditions in the Trench.

Introduction--The name Puerto Rico Trough has been applied to the depression, including the Milwaukee Depth and Brownson Deep of early charts, about 80 mi north of Puerto Rico and extending east from the Bahama Banks to Anegada Passage. In this report the term Puerto Rico Trench is used for the steep-sided, "flat" floored, longitudinal depression that marks the major axis of the Trough.

Soundings used in this study were made on continuous recording-depth sounders based on the standard vertical sounding velocity of 800 fm/sec. Figure 1 is a master plot of the sounding tracks which give the control for the contoured chart, Figure 2. Much of the detail was taken from records made by the author on the Edo sonic sounder Model AN/UQN 1B, modified by an additional stylus which permits recordings on a greatly exaggerated scale [NORTHROP, 1953]. The navigation for the exaggerated profiles should be good within plus or minus one mile as a continuous DRE (dead-reckoning equipment) plot was kept adjusted to twilight star fixes, morning, noon, and afternoon Sun lines, and the few good loran fixes which were obtained using sky waves at night. Additional soundings on a similarly modified echo sounder and good navigational control are needed before a smaller contour interval chart would be practicable. A 200-fm contour interval was selected for this report because it is believed there is sufficient sounding data in the area to justify it.

Bathymetry--The Puerto Rico Trench is from five to ten miles wide and is separated from the Nares Basin to the north by a steep divide which rises to 2900 fm (Fig. 2 and 3). The floor of the Trench is essentially flat at 4350 fm, A - B of Figure 4, although some crossings indicate greater depths, and one crossing shows a 15-fm rise in the center of the Trench. Sediment cored from the floor of the Trench shows layers of abyssal red clay and of calcareous deep-sea sands containing shallow water fossils. This suite of sediments is restricted to the Trench, the north and south walls showing only red clay [ERICSON and Others, 1952].

The southern limit of the Trench is abutted by several seamounts and indented by submarine canyons down which the calcareous shallow water sediments may be transported by turbidity currents. The row of seamounts curves from the slope north of the Virgin Islands northwestward and then comes around to east-west, descending at the same time rather irregularly from 2700 to 3700 fm.

Much of the sediment on the western part of the Trench must come from the Bahama Banks and surrounding limestone cays. Another source is from the shoals of Mona Passage from which Aquadilla Canyon runs approximately north for 60 mi, terminating in 4100 fm (Fig. 2), giving it a gradient of 400 ft/mi. The canyon is bordered on the east by a ridge extending out from Punta Borinquen, and on the west by a 400-fm seamount.

Twenty miles east of Punta Borinquen the Arecibo Canyon extends northward from the mouth of the Arecibo River and on out into 4000 fm. The Arecibo River, like the Manati, the Plata, and the Bayamon Rivers, is an extended consequent stream that stems from above the coastal plain in the Cordillera Central of Puerto Rico and flows through an area where the annual rainfall is from

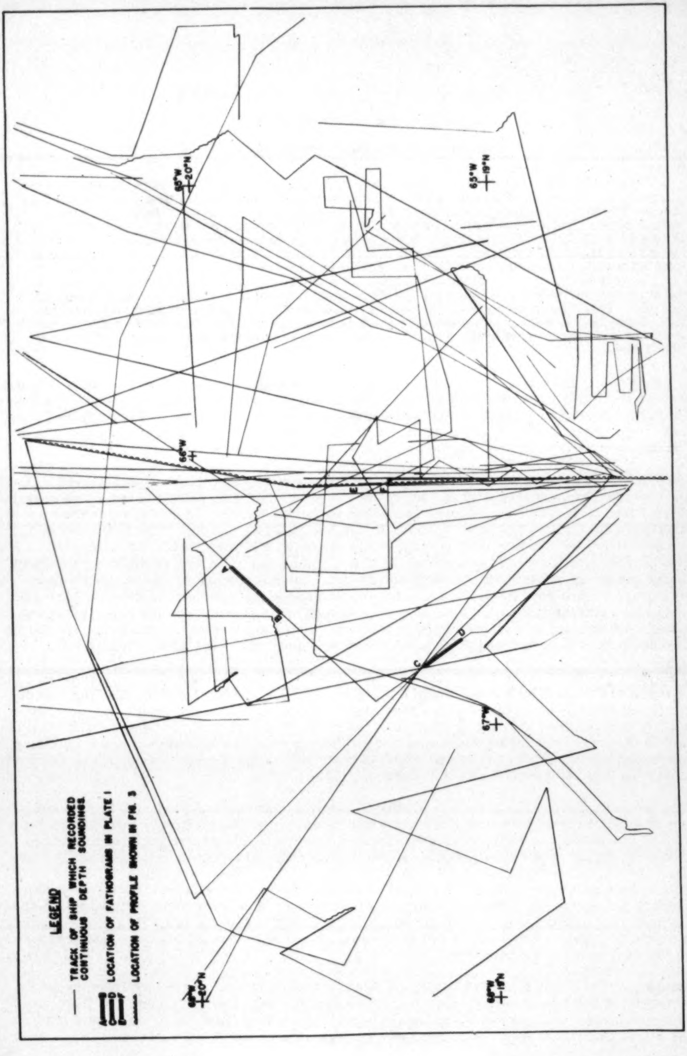
LEGEND
TRACK OF SHIP WHICH RECORDED CONTINUOUS DEPTH SOUNDINGS
A B C D E F LOCATION OF FATHOGRAMS IN PLATE I
LOCATION OF PROFILE SHOWN IN FIG. 3
A
B
C
D
E
F
65°W 20°N
65°W 19°N
66°W
67°W
68°W 20°N
68°W 19°N

Fig. 1--Location of continuous sounding tracks, overlay for Figure 2

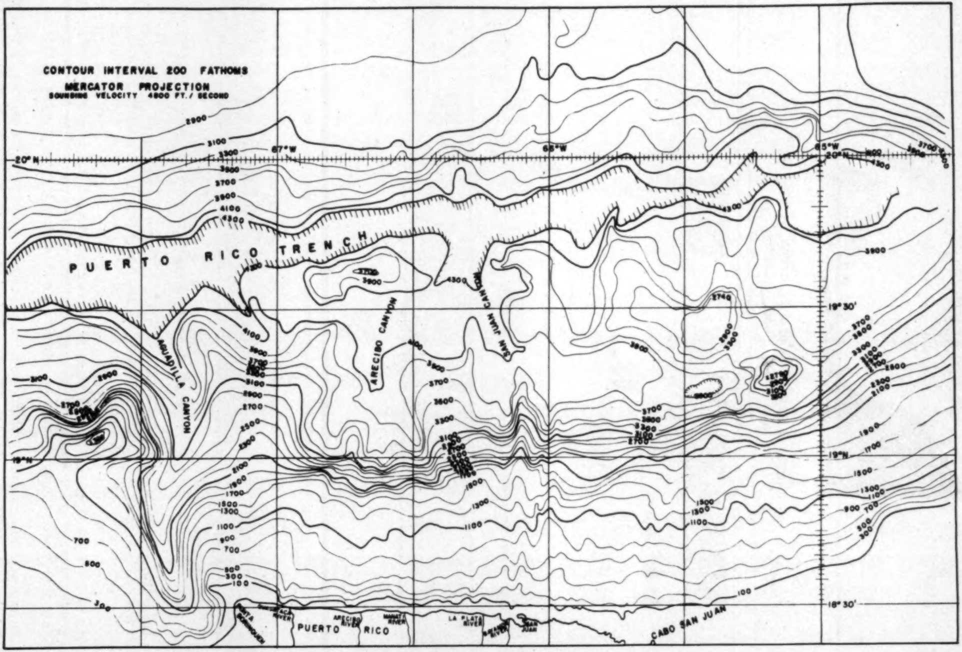
CONTOUR INTERVAL 200 FATHOMS
MERCATOR PROJECTION
SOUNDING VELOCITY 4800 FT./ SECOND
20° N
19° 30'
19° N
18° 30'
67° W
66° W
65° W
PUERTO RICO TRENCH
AGUADILLA CANYON
ARECIBO CANYON
SAN JUAN CANYON
PUNTA BORINQUEN
ARECIBO RIVER
MANATI RIVER
LA PLATA RIVER
SAN JUAN
PUERTO RICO
CABO SAN JUAN

Fig. 2--Bathymetric chart of the Puerto Rico Trench

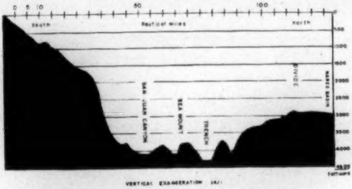

Fig. 3--Bathymetric profile across the Puerto Rico Trough north of San Juan

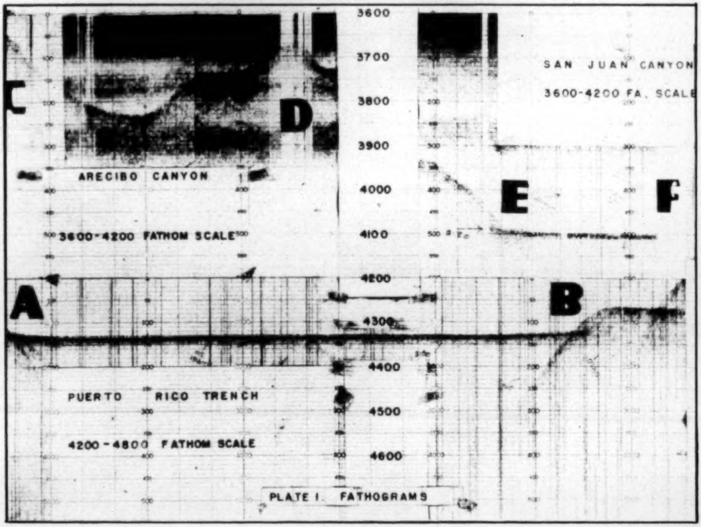

Fig. 4--Fathograms

90 to 110 inches [LOBECK, 1922]. The Arecibo River has cut a deep channel in limestone along its course and rises 30 to 40 ft in flood, inundating the towns and farms along its flood plain. It may be that the sediment-laden flooded stream starts turbidity currents flowing down its offshore submerged canyon and deposits calcareous sediment in the Trench. A crossing of the Arecibo Canyon is shown on C - D of Figure 4. At this crossing it has a flat floor at 3830 fm about a mile wide and sides sloping at six degrees with the horizontal. Seaward of this crossing the canyon flows out onto a 4100-fm plain where a turbidity current might be ponded before flowing into the Trench.

There appear to be several tributaries to this canyon system, possibly heading up into the mouth of the Plata or Manati Rivers. However, there are not enough soundings in the area to draw such conclusions with certainty. Between these major canyons there is a series of smaller canyons that incise the submerged coastal plain, but the area is not surveyed accurately enough as yet to include them in this report. It is not surprising that these canyons exist, inasmuch as the slope is about five degrees out to the 1500-fm curve and increases to ten degrees between the 1500 and 4000-fm contours. Slopes of this order of magnitude are well within the range used by KUENEN [1950] to produce turbidity currents experimentally in the laboratory.

Below the 4000-fm curve both the Arecibo and San Juan Canyon systems debouch into an east-west trending basin which is separated from the Trench by a row of seamounts, except at the mouth of San Juan Canyon where the 4300-fm contour is indented (Fig. 2). The setting of this east-west basin in relation to Puerto Rico and the Trench is shown in the representative profile, Figure 3. In Figure 4, E - F shows the fathometer record across this basin, where it appears to join San Juan Canyon. The bottom of the basin is level at 4100 fm, about five miles wide, and abruptly terminated to the south by the topographic rise of Puerto Rico.

Conclusions--The Puerto Rico Trench is a depression five to ten miles wide and roughly 400 mi long, extending east-west about 80 mi north of Puerto Rico. On its floor are layers of sediment containing shallow water foraminifera with up to 74 pct $CaCO_3$ which alternate with layers of abyssal red clay. The latter is normal for the depth, and the anomalous shallow water sediments are transported there probably from the south and west presumably by turbidity currents. Some of the submarine canyons down which these turbidity currents flow head into extended consequent streams that rise in the mountains of Puerto Rico and pass through limestone areas of heavy rainfall. Other canyons do not seem to have landward extensions and may be tributaries of the larger ones. The canyons debouch into a series of east-west trending basins at 4000 fm where a certain amount of ponding of the sediments must take place before they spill over into the Trench itself. Such a process tends to level the topography and fill up the depression with sediment.

The prominent negative gravity anomalies that parallel the major axis of the Trench indicate that a tectogene underlies the depression [HESS, 1933]. It is now becoming evident from studies such as this that geological strata which contain graded sandstone layers similar to the anomalous deep sea sands of the Puerto Rico Trench are not evidence of shallow water environment, but rather they are confirmed evidence of turbidity current deposition at abyssal depths.

Acknowledgments--The work was done under Contract N6-ONR-27135 between Columbia University and the Office of Naval Research. The help of J. E. Nafe and Gordon Becker, co-workers on the project, is gratefully acknowledged along with that of H. H. Hess of Princeton University who critically read the manuscript before publication. J. B. Hersey of the Woods Hole Oceanographic Institution kindly provided Barbara Mason's chart of the area.

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EFFECT OF A HARDWOOD FOREST CANOPY ON RAINFALL INTENSITIES

G. R. Trimble, Jr., and Sidney Weitzman

Abstract--Ground rainfall intensities and throughfall were measured under a fully-stocked hardwood forest in West Virginia over a period of one year. Maximum 5- and 15-min intensities were compared with similar measurements made in the open. The results were analyzed separately for winter and summer conditions; that is, bare canopy versus canopy in full leaf. Regression equations were calculated for estimating intensities and throughfall under canopy from rainfall measurements made in the open. The study shows that low rainfall intensities are reduced more by summer canopy, and high intensities are reduced more by winter canopy. Throughfall is reduced by canopy interception approximately the same amount in both summer and winter.

Introduction--A study was made to determine how a full hardwood forest canopy changes rainfall intensities as rain passes through it. This information is needed to fill a gap in our knowledge of the role of forest vegetation in watershed management. Rainfall intensity is one of the factors that determine the erosion potential of rainfall. Other factors are drop velocity and drop size. COOK [1936], HORTON [1940], LAWS [1940 and 1941], LAWS and PARSONS [1943], CHAPMAN [1948], and ELLISON [1949] have reported on these other factors. LAWS [1941] has shown that water drops at least up to six mm in diameter, and probably of any size, attain 95 pct of maximum velocity after falling only 7.8 m. Most forest tree canopies are this high above the ground by the time the stand is 30-35 years old. Thus, unless modified by undergrowth, the effect of most forest canopies on drop velocity is negligible.

CHAPMAN [1948] showed that in a red pine plantation, the effect of canopy was to collect and concentrate small drops, releasing them to throughfall as larger drops. Under these conditions, the erosion potential of rainfall was increased under canopy. His study also contained some limited data on intensities, taken incidental to his study of drop size, which indicated that after the canopy was wet, intensities in the open and beneath the canopy were about equal. Except for Chapman's report, the literature contains no data on the effect of forest canopy on rainfall intensities.

Area studied--The authors' study was made on the Fernon Experimental Forest near Parsons, West Virginia. The general area is rugged and mountainous, typical of approximately 23.5 million acres of forest land in West Virginia, Kentucky, western Maryland, and southwestern Pennsylvania. The study site is located on the middle of a short slope at an elevation of 2400 ft. It faces south. The slope is approximately 20 pct.

The climate is characteristic of the high country west of the Allegheny Front in West Virginia. The mean annual temperature is between 45°F and 50°F. The prevailing wind is from the west. This is true for both storm and non-storm periods. Annual precipitation is approximately 60 inches; it is well distributed throughout the year. July averages the most rainfall, November the least. Approximately two to six inches fall as snow in the winter. Maximum rainfall intensities generally occur in the summer. The highest five-minute maximum during the year of the study was 3.36 in/hr on July 6, 1952. According to YARNELL [1935] this general area can expect a five-minute intensity of about 4.2 in/hr on a two-year frequency rate.

The study area is covered with a fully-stocked, even-aged stand of mixed hardwoods about 50 years old. Among the species comprising the stand are northern red oak, yellow-poplar, red maple, black locust, blackgum, black birch, and cucumber magnolia. Most of the tree canopy occupies an area 30 to 70 ft above the ground; there is some high understory. In general, the forest type and condition represent millions of acres of hardwood forest in the southern Appalachian Mountains.

Measuring rainfall intensity--Rainfall intensities and the amount of storm rainfall in the open were compared with intensities and throughfall under a canopy. (Throughfall is the amount of precipitation falling through the canopy to the Earth, not including stemflow. In this study throughfall was measured at rain-gage height rather than on the surface of the forest floor.) Friez weighing and recording rain gages were used.

A continuous rainfall record was obtained on a chart mounted on a cylinder activated by an eight-day clock. Twenty-four hour gears were used to obtain a scale record on the chart as large as possible to facilitate computations and reduce office errors in determining intensities (see Fig. 1). Charts were changed once a week, at which time the clocks were checked and the gages were tested and adjusted for correct weighing.

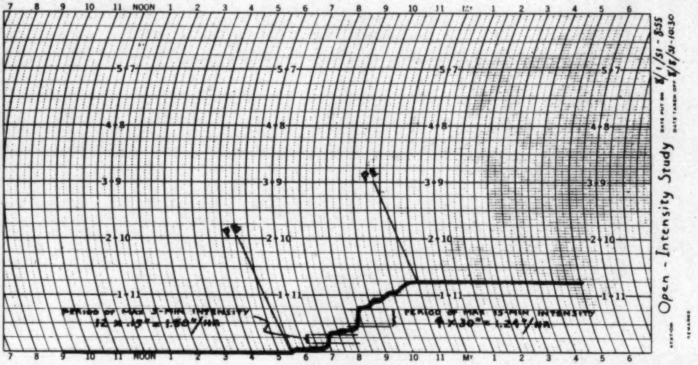

Fig. 1--Rainfall recording chart used in the study; this chart shows the rainfall recorded for one storm

The gage in the open was installed in the center of a half-acre clearing. The records obtained on this gage were the standard with which the canopy records were compared. Five gage sets were located at random under the adjacent forest canopy (see Fig. 2). The location of the canopy gages was permanent for the period of the study.

The study period was divided so as to observe summer and winter conditions separately. Records for the summer period were taken from August 10 to October 7, 1951, and from May 19 to July 6, 1952. The canopies were fully in leaf during these periods. Winter rainstorms were recorded from November 6, 1951, to April 28, 1952, while the trees were entirely bare. Records of storms that consisted entirely or partly of snowfall were not used. Figures 3 and 4 show summer and winter canopies over one of the gages. These canopies are typical of the stand. In the analysis of the data, each chart was marked to show the beginning and end of the storm period and the beginning and end of maximum 5- and 15-min intensities. Intensities for these periods were then converted to an hourly basis.

Effect of canopy--Differences in rainfall intensity between the gage in the open and the gages under the tree canopy were computed for 28 storms in the summer period and 31 storms in the winter period. ("A storm is considered as a period of precipitation separated by at least six hours from any other period in which precipitation occurs" [HURSH, 1940].) A wide range of intensities and storm sizes was recorded. The range, as recorded by the open gage, is shown in Table 1. Average maximum 5- and 15-min intensities and average rainfall for all storms measured are shown in Table 2. Considerable variation was found, in both intensity and throughfall, among the

Table 1--Range in maximum intensities and total rainfall for storms measured by gage in open

Item	5-min max		15-min max		Total storm	
	Summer	Winter	Summer	Winter	Summer	Winter
	in/hr	in/hr	in/hr	in/hr	in	in
Maximum	3.36	2.40	3.00	1.08	1.23	1.45
Minimum	0.10	0.12	0.10	0.06	0.05	0.04

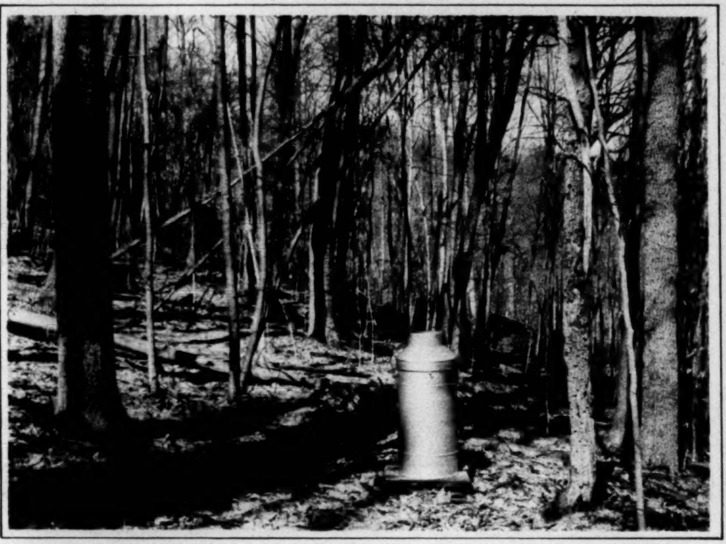

Fig. 2--Six Friez rain gages were used; five, like this one, were placed under the tree canopy, one was placed in the center of a half-acre clearing

gages under tree canopy. Table 3 gives coefficients of variation for the canopy gage averages. The data show that coefficients of variation are considerably less for winter conditions than for summer conditions. Table 3 also indicates that variation tends to be greater for storms of low total precipitation.

Table 2--Average maximum 5- and 15-min intensities and rainfall from all storms

Item	5-min max		15-min max		Total storm	
	Summer	Winter	Summer	Winter	Summer	Winter
	in/hr	in/hr	in/hr	in/hr	in	in
Open gage	1.18	0.64	0.72	0.37	0.48	0.57
Average of canopy gages	1.00	0.52	0.57	0.31	0.36	0.45

During both summer and winter periods, one location gave intensities and throughfall that were consistently lower than the canopy averages. Another location gave intensities and throughfall that were consistently higher than average. The other three locations gave results very close to the average. In all cases, individual gage averages, for either the summer or the winter period, were less than the average value in the open and closer to the canopy average than to the value obtained in the open.

Occasionally an individual canopy gage registered higher intensities than the open gage, and in a few summer storms a canopy gage caught more rainfall than the open gage. Forest canopy reduced intensities and throughfall for both summer and winter periods. The difference between open gage readings and canopy averages were subjected to a t test. This test showed that there was less than one chance out of 100 that such differences were due to chance. The values for t are shown in Table 4.

Fig. 3--Typical summer tree canopy at gage site

Linear regression equations were fitted to the data to show relationship between rainfall in the open and under a full hardwood canopy. Equations were also calculated for throughfall. Y = estimate of average rainfall under canopy; X = measurement in the open.

Summer conditions

Max 5-min intensities	$\hat{Y} = 0.9758X - 0.0773$	Stand. Err. $\pm$ 0.0017
Max 15-min intensities	$\hat{Y} = 0.9477X - 0.0611$	Stand. Err. $\pm$ 0.0007
Throughfall	$\hat{Y} = 0.8092X - 0.0164$	Stand. Err. $\pm$ 0.0006

Winter conditions

Max 5-min intensities	$\hat{Y} = 0.8524X - 0.0118$	Stand. Err. ± 0.0014
Max 15-min intensities	$\hat{Y} = 0.8072X + 0.0067$	Stand. Err. ± 0.0013
Throughfall	$\hat{Y} = 0.7891X - 0.0062$	Stand. Err. ± 0.0011

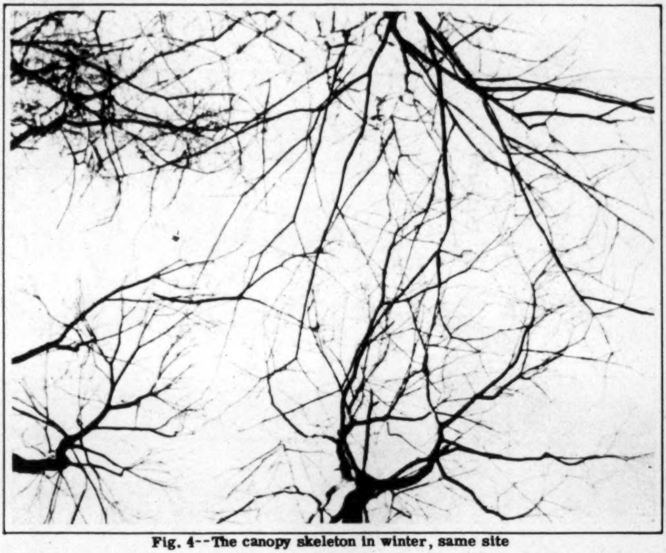

Fig. 4--The canopy skeleton in winter, same site

Table 3--Coefficients of variation for canopy gage averages, by season and storm size

Storms			5-min max		15-min max		Throughfall	
Size	Number		Summer	Winter	Summer	Winter	Summer	Winter
	Summer	Winter						
in			pct	pct	pct	pct	pct	pct
Under 0.2	6	6	36.4	19.1	42.7	16.8	41.1	17.8
0.2 to 0.5	5	7	25.9	10.0	30.4	8.3	26.7	7.9
0.51 plus	8	17	15.6	14.7	15.9	9.3	23.2	7.7
Total or average	19[a]	30[a]	22.5	14.6	28.2	10.6	29.8	10.0

[a] Actually 28 storms were studied for the summer period and 31 storms for the winter period. However, during nine of the former and one of the latter, only one canopy gage was operating so there were no canopy averages.

Table 4--Values of t for maximum 5- and 15-min intensities and throughfall

Item	5-min max	15-min max	Throughfall	Value of t for probability level of 0.01
Summer	4.84	5.47	7.98	2.77
Winter	4.62	6.34	8.12	2.75

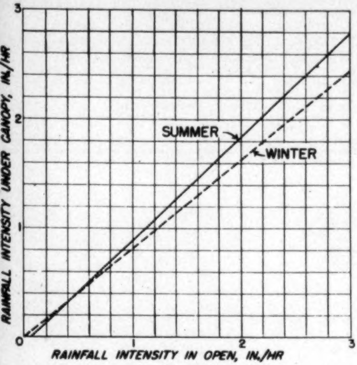

Fig. 5--Rainfall intensities under forest canopy, based on 5-min maximum storm intensities

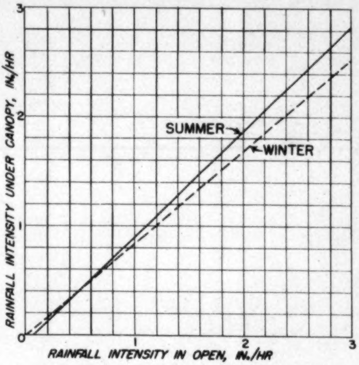

Fig. 6--Rainfall intensities under forest canopy, based on 15-min maximum storm intensities

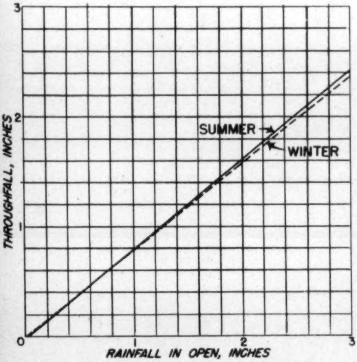

Fig. 7--Throughfall under forest canopies

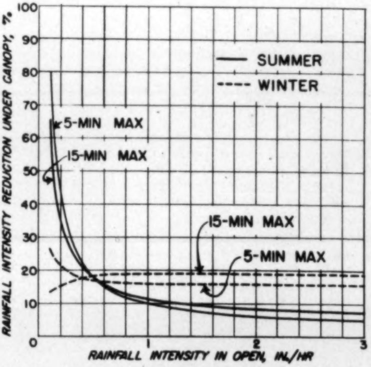

Fig. 8--Reduction of rainfall intensity by forest canopy

Based on these equations, Table 5 and Figures 5 to 8 show the intensities and throughfall under canopy for a wide range of open intensities and throughfall. Examination of these data leads to several important observations:

(1) Forest canopies reduce rainfall intensities as rainfall passes through the canopy. The amount of reduction differs by the season and rainfall intensity.

(2) As between summer and winter conditions, low intensities below approximately 0.5 in/hr are reduced more by summer canopy, and high intensities (above approximately 0.5 in/hr) are reduced more by winter canopy (see Fig. 5, 6, and 8).

(3) As shown in Table 5, the maximum reduction for high-intensity rainfall is less than 20 pct.

(4) Throughfall is reduced by canopy interception approximately the same amount in both summer and winter (see Fig. 7).

Table 5--Maximum rainfall intensities, and reductions due to canopy, for 5- and 15-min periods, determined by regression equations

Intensity in open	Intensity under canopy		Reduction in intensity due to canopy			
	Winter	Summer	Winter		Summer	
in/hr	in/hr	in/hr	in/hr	pct	in/hr	pct
5-min intensities						
0.10	0.073	0.020	0.027	27.0	0.080	80.0
0.30	0.244	0.215	0.056	18.7	0.085	28.3
0.50	0.414	0.411	0.086	17.2	0.089	17.8
0.75	0.627	0.655	0.123	16.4	0.095	12.7
1.00	0.841	0.899	0.159	15.9	0.101	10.1
1.50	1.267	1.386	0.233	15.5	0.114	7.6
2.00	1.693	1.874	0.307	15.4	0.126	6.3
3.00	2.545	2.850	0.455	15.2	0.150	5.0
15-min intensities						
0.10	0.087	0.034	0.013	13.0	0.066	66.0
0.30	0.249	0.223	0.051	17.0	0.077	25.7
0.50	0.410	0.413	0.090	18.0	0.087	17.4
0.75	0.612	0.650	0.138	18.4	0.100	13.3
1.00	0.814	0.887	0.186	18.6	0.113	11.3
1.50	1.217	1.360	0.283	18.9	0.140	9.3
2.00	1.621	1.834	0.379	19.0	0.166	8.3
3.00	2.428	2.782	0.572	19.1	0.218	7.3

It is obvious that a tree in full leaf offers a greater intercepting surface to rainfall than does the bare tree in winter. The fact that a canopy in full leaf shows less reducing effect on high-intensity rainfall than the winter canopy appears therefore somewhat unreasonable. The authors offer this explanation:

In summer, for a storm of given magnitude, the direct interception of rain by the tree skeleton (twigs, limbs, and trunk) is less than in winter because so much rain is first caught by the leaves. (Interception as used in this discussion is gross interception; it includes stemflow.) During intense rainfall the leaves are beaten or tip downward away from the connection to the twig so that practically all of the rain runs off and falls to the ground. Thus during periods of intense bursts, some of the rainfall that had been previously intercepted may be released as ground rainfall. During such periods it appears as though there is less interception than when the tree is bare and a greater part of the rain is caught directly by the tree skeleton. (Actually, the difference between summer and winter interception at high intensities involves only a small volume of water since these high intensities occur only infrequently and then for such short periods. For a five-minute burst at an intensity of 2.0 in/hr, the actual difference between summer and winter interception is 0.181/12 or 0.015 inch of water.)

On the other hand, when the rainfall intensity is low the leaves are not beaten into a drooping position and a greater proportion of the rain that falls on them runs down the leaf stem and becomes stemflow or is used to wet the leaves, twigs, limbs, and trunk. Thus for low-intensity rainfall, the reducing effect of canopy is greater in the summer. This reversal of relationships is illustrated in Figures 5, 6, and 8. At the point (0.5 in/hr) where the lines cross, winter and summer canopies reduce rainfall intensities to the same extent.

Interpreting the intensity equations in terms of interception tends to clarify this relationship, since the rate of interception is the reciprocal of ground rainfall intensity. Consider a storm with a maximum five-minute intensity in the open of 0.30 in/hr. The intensity equations indicate that the rate under canopy would be 0.22 in/hr in summer and 0.24 in/hr in winter. Conversely the rate of interception would be 0.08 in/hr in summer and 0.06 in/hr in winter. With a higher open intensity of 2.0 in/hr the rate under canopy would be 1.86 in/hr in summer and 1.69 in/hr in winter. Interception rates would be 0.14 in/hr in summer and 0.31 in/hr in winter. Thus for the higher intensities, the interception rates for summer and winter are reversed.

CHAPMAN [1948] measured 15-min intensities beneath a 29-year-old red pine plantation and found that they were approximately equal to intensities for the same period in the open. He measured these intensities for five storms during the period of rainfall after the canopy had become thoroughly wet and before rain in the open had abated. Why did his five measurements show no reduction of intensity due to canopy, while the authors' study with hardwoods in leaf showed a small but very significant reduction?

In the first place, other studies show that stemflow for conifers is lower than for hardwoods. ZON [1927] gives stemflow for conifers at 0.7-3.0 pct of precipitation and for hardwoods up to 15 pct. WILM and NIEDERHOF [1941] report stemflow for lodgepole pine as less than 0.1 pct of precipitation. Results to date of continuing studies in Pennsylvania by the Northeastern Forest Experiment Station (unpublished) show that hardwood stemflow in that area is between two and 15 pct. Under the conditions of Chapman's study, stemflow must have been very small. Differences in intensity between canopy and open then would have been very small indeed for a 15-min period and might easily not have shown up at all with so few samples.

It was thought that if the maximum intensity of rainfall came at the very beginning of a storm, the reducing effect of canopy would be much greater than it would be after the canopy was wetted. This would appear to be particularly true for five-minute maximum intensities when the leaves were out. It could conceivably be a source of large variation in estimating canopy intensities from open gages. Examination of the open gage charts, however, showed that maximum intensities rarely occurred at the beginning of a storm.

An attempt was made to determine the lag in the beginning and ending of maximum intensities and the beginning and ending of ground rainfall due to canopy interception. Undoubtedly such lags exist but they are so small that they were obscured by the time difference between gage clocks, which sometimes were five to ten minutes.

Conclusions--The results of this experiment on rainfall intensities under canopy, when supplemented by previous research on the effect of canopy on drop size and intensity, indicate that the physical presence of a forest cover has only a limited value in reducing the erosion potential of rainfall as it strikes the forest floor. Its greatest effect is under summer conditions at low intensities when the erosion potential of rainfall is at its lowest.

However, this is not meant to imply that the forest does not play an important role in reducing erosion. As demonstrated by GLEISSNER [1914] and LOWDERMILK [1931], the forest floor remains the main bulwark against runoff and erosion.

The major role of the forest in reducing erosion is an indirect one; it furnishes a layer of litter and humus that provides mechanical protection and reduces the erosibility of the soil. Reduced erosibility results from improved soil structure, which promotes infiltration and decreases the detachability of the soil particles. It has been demonstrated by SARTZ and HUTTINGER [1950], TRIMBLE and TRIPP [1949], and TRIMBLE [1952] that there is a causative relationship between a well-stocked forest stand and a highly absorptive forest floor.

KITTREDGE [1948] quotes a number of studies on infiltration rates which show that water enters the soil under a forest cover much faster than it enters the soil under other types of cover. Data collected in flood-control surveys by the United States Department of Agriculture in the Northeast (unpublished) indicate that the infiltration rate (f_c values; f_c is the final constant or minimum infiltration capacity) under undisturbed hardwood stands on medium-texture soils, similar to those in the authors' study area, is approximately 2.4 in/hr. The surveys determined that infiltration rates (f_c values) for identical soils, but for other conditions of cover are: clean-tilled, 0.26 in/hr; good pasture, 0.57 in/hr; and good hayland, 0.58 in/hr.

Studies to determine the use of forest cover in preventing erosion should place emphasis on the relationship of the forest to soil factors rather than to rainfall characteristics.

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OPEN CHANNEL FLOW OF WATER-AIR MIXTURES

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Abstract--The problem is analyzed in analogy with that of sediment transport and is partially solved. While it has not been possible as yet to predict the air content of the mixture for a given state of flow or of turbulence, the vertical distribution of air in a turbulent water mass was found to follow the laws of suspension. The change of the average flow velocity and flow depth of an open channel flow involving air-water mixtures was predicted theoretically as a function of the air concentration. The predicted relationship was checked by measurements in model channels.

General introduction--The problem arose when the authors were asked to predict the water surface in the pit of an impulse turbine. When the turbine is operating normally, most of the jet energy is dissipated in the wheel and the water drops into the pit at low velocity. In case of a sudden reduction of the load, however, part or all of the discharge is diverted from the wheel by deflectors and hits the pit wall and from there the pool at high velocity. The pool water is stirred up violently. The resulting high turbulence level in the water together with the direct action of the impinging jets cause a large amount of air to enter the water in the form of bubbles and to stay there in suspension until the turbulence has died down sufficiently in the discharge channel to permit the air to be released.

Although there exists today a rather large literature on air entrainment in water, no basic theory of the problem has been developed. It is understood, however, that the air enters the water in the form of bubbles and remains in that form until it escapes through the water surface. These air bubbles have a density greatly different from that of the surrounding water and can be prevented from immediate rise to the surface only by a high turbulence of the flow. This behavior is very similar to that of sediment in water, the solid particles which are usually heavier than water and are moved along with the fluid flow in various ways. Since this latter problem is somewhat better known than that of air entrainment, it appears to be appropriate to describe first the different basic elements of sediment motion in water, and to see then if these same elements can be used to describe air entrainment.

The corresponding sediment problem is that of a turbulent flow which moves over a large sediment deposit [EINSTEIN, 1950]. This flow dislodges a larger or smaller number of deposited particles, depending on the flow and sediment characteristics, and moves these particles as bed load along the bed. The rate of this bed-load movement is described as an equilibrium between the rate at which sediment particles are scoured from the bed and redeposited into it. The sum of all the moving bed-load particles together with the surrounding water determine a sediment concentration near the bed. This water-sediment mixture is under favorable conditions of high turbulence mixed with the remaining flow. Thus the sediment particles with a sufficiently low settling velocity are thrown into suspension. These solid particles assume the horizontal flow velocity of the surrounding water and usually move larger distances with the flow before they settle back down to the bed. But there is not only an effect of the flow on the sediment; also the flow is influenced by the moving sediment. Both the frictional losses and the density of the flow are affected. Similarly, one may establish the following.

Analysis of the air entrainment problem

Stability condition of the water surface--Whenever the turbulence velocities are sufficiently high it occurs that water masses will approach the surface at velocities which enable them to break through the water surface, overcoming gravity and surface tension, under the influence of their own inertia. When they drop back into the main water body, they are apt to entrap some air which will form bubbles inside the water. These bubbles will move with the water as does the bed load until they rise again to the surface and break through it. It is anticipated that again an equilibrium equation can be established between the entrapment and the release of air through the water surface, defining an equilibrium air concentration near the surface as a function of the turbulence conditions. The formal establishment of such an equilibrium condition has not been possible as yet.

The influence of impinging jets--The jets which enter the water body through the water surface do not only create turbulence in the water but they may also entrain additional air into the water. If the jets are compact, such air entrainment will occur at their boundaries; if the jets are broken up into droplets, they entrain air in large quantities within their own volumes. It is not known today if this additional air which the jets contribute to the flow directly can maintain itself in the water for any significant length of time over the amount derived from the exchange equilibrium at the free water surface.

Suspension of air bubbles--The description of suspension is different from that with sediment mainly because of the different flow pattern. When sediment is suspended in a flowing stream, the turbulence which provides for the vertical flow velocities is created by the frictional flow along the sediment bed. This turbulence pattern is determined by von Karman's similarity condition and therefore varies with the elevation in the flow. The turbulence visualized in our air entrainment problem, on the other hand, is originally created by the jets and then slowly dies out. This turbulence is in character isotropic and evenly distributed over the entire water depth. The mixing length ℓ and the exchange velocity q_e may thus be assumed to be constant over the water depth. If we introduce the vertical distance y of a point below the water surface, we may write for the air exchange q_a through a horizontal unit area at y

$$q_a = q_e (c \pm \Delta c) = q_e (c \pm 0.5 \ell dc/dy) \quad (1)$$

where the positive sign appears to exchange in the upward direction and the negative sign to that in the downward direction, ℓ is the constant mixing length. The equilibrium condition for air exchange can then be established in the form that the downward exchange minus the upward exchange must compensate for the general rise of all air bubbles with the velocity v_s with respect to the surrounding water

$$q_e (c - 0.5 \ell dc/dy) - q_e (c + 0.5 \ell dc/dy) = c\, v_s \quad (2)$$

Neglecting higher than the first terms of $0.5 \ell dc/dy$, this may be written as

$$q_e \ell dc/dy = - c\, v_s \quad (3)$$

$$dc/c = [- (v_s)/q_e \ell)]\, dy \quad (4)$$

and after integration

$$\log_e (c/c_o) = - (v_s\, y)/(q_e \ell) \quad (5)$$

where c_o is the concentration at the water surface $(y = o)$. This may be written as

$$\log_e (c) = \log_e (c_o) - (v_s\, y)/(q_e \ell) \quad (6)$$

which shows that the equation represents a straight line relationship between c and y in a semi-logarithmic graph.

To check this law a rather crude experiment was completed. Using a nozzle, a jet of water was introduced into a small container with 9 1/2 × 9 1/2 inches cross-section and about one foot in height. The pressure to the nozzle was adjustable from 0 to 130 lb/in^2. The jet carried air into the water and produced an air and water mixture in the container. Now, using a sampler, the air concentrations were measured from point to point on a vertical and the results plotted on a semi-log paper as shown in Figure 1. The result is approximately a straight line which shows that the concentration along the vertical axis follows the distribution law of isotropic turbulence fairly well. The first measurement was made at depth $a = 0.2$ ft from the water surface and the other concentrations compared with that at a. Eq. (5) may be rewritten as

$$\log_e (c_y/c_a) = - [v_s (y - a)]/\epsilon \quad (5a)$$

where c_y and c_a are the concentrations of air at elevation y and a respectively, v_s is the rising velocity of air bubbles and $\epsilon = q_e \ell$ is a diffusion coefficient. Now, knowing concentrations at a and y, one can determine the rising velocity v_s from the slope of the line and hence the bubble size may be found, provided that, ϵ is known for the given turbulence condition beforehand.

Effect of the suspended air on the flow characteristics--In a given open channel cross section a discharge Q may flow at any water depth provided that the available energy permits the necessary

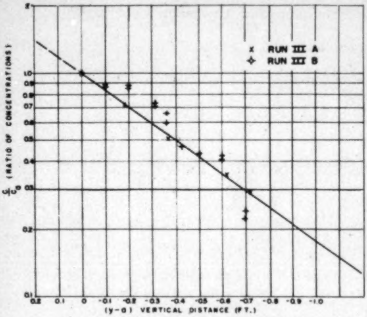

Fig. 1--Relation of concentration to vertical distance

velocity of flow to be attained. The normal hydraulics of the back-water curves permits the prediction of the flow depth in the sections of a channel if the depth at one section is given. In our problem the question is asked how the water depths in various sections of a channel can be predicted in which the air content changes from section to section. For this derivation the following assumptions are made:

(a) In the interest of an easier mathematical treatment, the air is assumed to be evenly distributed over each vertical, in contrast to the distribution derived in the previous paragraph.

(b) All air is supposed to be dispersed over the section in the form of small bubbles, such that the horizontal velocity of the air may be assumed to be equal to that of the surrounding water.

(c) Again in the interest of easier mathematical treatment, the channels are assumed to have rectangular cross sections of constant width and negligible slope.

(d) Only steady flow conditions are studied (constant water discharge).

(e) The flow velocities in the channels under consideration are low. If the channels are relatively short, the friction losses are small and can thus be neglected. In a first approximation, the flow is assumed to be frictionless.

The following notations are used:

d = the water depth of the air-water mixture
d_o = the water depth at zero air content
v = the flow velocity of the air-water mixture
v_o = the flow velocity at zero air content
$q = d \cdot v$ = the discharge of mixture per unit of width
$q_o = d_o \cdot v_o$ = the water discharge per unit of width ($\rho = 1$)
g = the acceleration due to gravity
W = the weight of the unit volume of water
ρ = the volume ratio of water content to the water-air mixture ($0 \leq \rho \leq 1$)

The assumptions of frictionless flow are equivalent to those of constant energy. As long as the gradient of ρ, v and d in the direction of flow are finite, the equation of motion can be given either in the form of an energy equation or in that of a momentum equation. The latter form is better suited for the case under consideration as applied to a short increment of flow dx. For this the momentum equation can be given in the form

$$d\,F(\rho, d)/dx = -d\,M(\rho, d, v)/dx \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

(see Fig. 2) where $F(\rho, d)$ is the pressure force in the cross section, the only type of force involved

$$F(\rho, d) = W/2\ \rho\, d^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

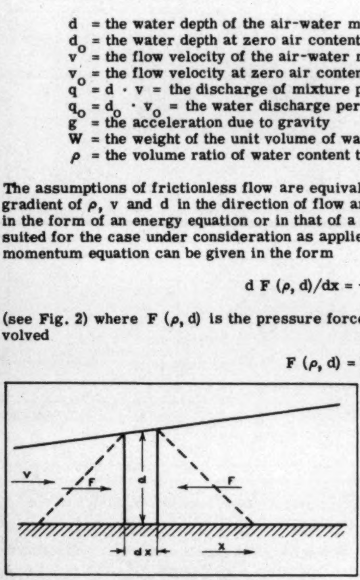

Fig. 2--Sketch indicating basis for momentum equation

and where $M(\rho, d, v)$ is the momentum of the discharge passing through a cross-section per second

$$M(\rho, d, v) = -\ W/g\ \rho\, dv^2 \quad \ldots\ldots \quad (9)$$

all expressed per unit width. The negative sign expresses the relative directions of the increments. This equation can directly be integrated into

$$F + M = W/2\ \rho\, d^2 + W/g\ \rho\, dv^2 = \text{constant} \ldots \quad (10)$$

In addition, the equation of continuity can be established indicating a constant water flow

$$q_o = dv\rho = \text{constant} \qquad (11)$$

By combination of (10) and (11) and by introduction of the Froude numbers F_o for $\rho = 1$

$$F_o = (v_o^2)/g\,d_o \qquad (12)$$

it is possible to give ρ as a function of (d/d_o)

$$\rho = (d_o/d)^2 \left[(1/2 + F_o) \pm \sqrt{(1/2 + F_o)^2 - 2\,F_o\,d/d_o}\right] \qquad (13)$$

and in function of (v/v_o)

$$\rho = (v_o/v)^2 \;[1 + 2\,F_o\,(1 - v/v_o)]^{-1} \qquad (14)$$

These relationships are given for the range $0 \leq \rho \leq 1$ and for some characteristic F_o values in Figure 3. Corresponding points of the graph show equal F_o, equal ρ and satisfy the modified (11)

$$(d/d_o)\,(v/v_o)\,\rho = 1 \qquad (15)$$

which uses the relationship $q_o = v_o\,d_o$ for $\rho = 1$.

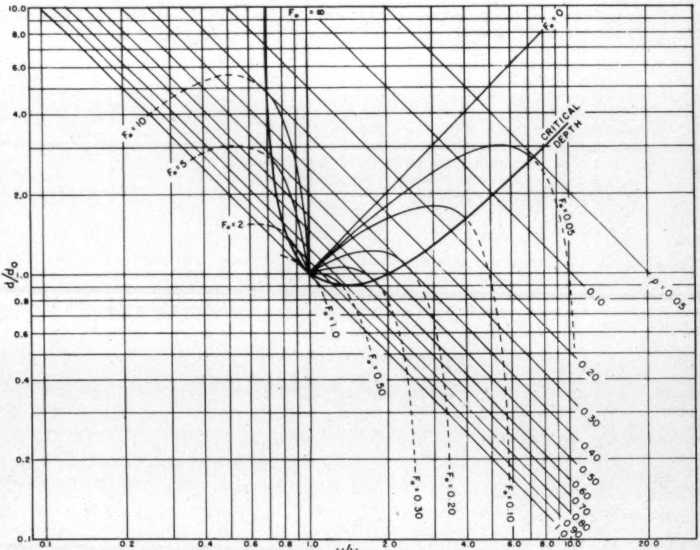

Fig. 3--Average depth of flow as a function of average flow velocity for different air entrainments and Froude numbers of flow

Eq. (13), (14), and (15) are shown graphically in Figure 3 and may be interpreted as follows: (15) gives directly the possible lines for various density ratios ρ as straight 45° lines in a log-log graph. Either of the two other equations or any combination of the two permits the point-by-point tracing of the lines for constant F_o, that is, for all the possible combinations of v, d and ρ values in a flow with constant energy, but variable air content.

This type of flow may be expected to exist in the canals draining the pits of high head impulse turbines, especially when the turbines operate under conditions of partial or total load rejection. Under these conditions, the water jets hit the pool at high velocity and create there a condition of high turbulence. This high turbulence level will persist in the entrance of the discharge channels which drain the pits and will only slowly die down along these canals. The condition of small energy loss is usually fulfilled in these canals for reasons of efficiency, such that the results of the theoretical prediction may be supposed to describe well the actual flow conditions. In that flow the point $v/v_o = 1$; $d/d_o = 1$ represents a downstream flow condition where the turbulence has sufficiently died down to permit all air to escape. At this point the Froude number v^2/gd assumes the value F_o. Following the corresponding curve in Figure 3, until the curve marked "critical depth" is intersected, all possible flow conditions are encountered. At critical depth the highest possible air content is reached for the given energy level. The dashed extension of the curves beyond this point has no practical significance in this case. It may be seen from Figure 3 that for values of F_o near unity only very small ranges of ρ can exist, while this range increases with increasing deviations of F_o from unity. This fact leads to the interesting question, what might happen if the value near the pit, which depends on the turbulence only, is smaller than the minimum value at critical for the particular flow in the downstream channel. One possible solution for that case is a flow with higher energy near the pit. This flow would be shooting with a hydraulic jump making the change to the final F_o curve. The excess energy would be lost in this jump. Jumps of this type were actually observed in the model.

A short remark is in place about the nomenclature critical depth for the limiting curve of Figure 3. Where it is customary to call an open channel flow with minimum energy constant critical, this curve represents actually the curve of minimum ρ as a maximum air content. This value exists at a value of

$$(v/v_o)_{crit} = (1 + 2\ F_o)/3\ F_o \quad \ldots\ldots\ldots\ldots \quad (16)$$

as may easily be derived from (14) for $(d\rho)/[d\ (v_o/v)] = 0$. For this value one derives

$$\rho_{crit} = 27\ F_o^2/(1 + 2\ F_o)^3 \quad \ldots\ldots\ldots\ldots \quad (17)$$

and from this and (15)

$$(d/d_o)_{crit} = (1 + 2\ F_o)^2/(9\ F_o) \quad \ldots\ldots\ldots\ldots \quad (18)$$

With this value one may derive the Froude number at critical conditions, which is

$$F_{crit} = F_o\ (v/v_o)^2_{crit}\ (d_o/d)_{crit} = 1 \quad \ldots\ldots\ldots\ldots \quad (19)$$

indicating that this condition of minimum density is actually a critical flow condition in the conventional sense. The formulas were checked against the experimentally obtained values at a model 1:20 and the correlation was found to be good.

To measure air concentration and distribution in air water mixture a special sampler was constructed, as shown in Figure 4. Before each run the separation chamber is filled with water. For this purpose a gear pump was used with valves V-1, V-3, and V-4 open, and V-2 closed. When the chamber was filled, valves V-3 and V-4 were closed. With valves V-1 and V-2 open, a constant rate of clear water is drawn from the chamber by the gear pump. The outgoing water is replaced by the same volume of air and water mixture. When the volume of air, separated from the mixture in t seconds is V_a and the volume of clear water pumped out during the same time t is

$$V_w = Q_p\ t$$

where Q_p is the pump discharge, then

$$C_a = (V_a/Q_p\ t)\ 100$$

C_a is the percentage of air in the air water mixture. From experience with sediment samplers it may be expected that the sampler pipe opening should be pointed against the flow and the velocity in the pipe should be the same as the velocity of the flow. This can be reached by adjusting the control valve V-2.

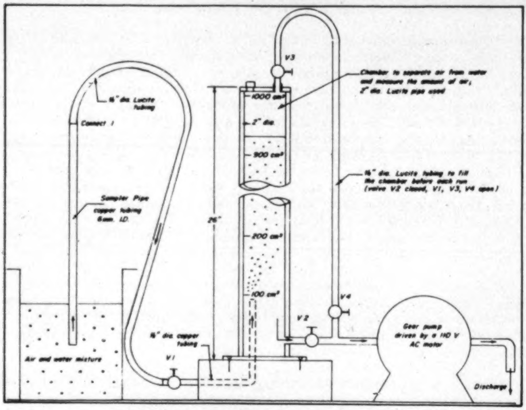
V3
Chamber to separate air from water and measure the amount of air; 2" dia. Lucite pipe used
¼" dia. Lucite tubing
Connect I
1000 cm³
2" dia.
900 cm³
¼" dia. Lucite tubing to fill the chamber before each run (valve V2 closed, V1, V3, V4 open)
Sampler Pipe copper tubing 6mm. I.D.
26"
200 cm³
100 cm³
V4
V2
Gear pump driven by a 110 V AC motor
¼" dia. copper tubing
V1
Air and water mixture
Discharge

Fig. 4--Air-water mixture sampler

The air concentrations were measured along verticals on center-line of the channels and the average values for each of the verticals were found by integration. The water-surface elevation was obtained by using point-gages. To investigate the flow pattern under different air concentrations two different nozzle directions were used. (1) Water jets rejected against the wall of the pit, as in the condition for the designed Alcan power plant. (2) Water jets rejected down against the bottom of the turbine pit. This condition introduced maximum amount of air into the flow.

Reference water-surface elevation for the values y_o, v_o, were obtained with the nozzles removed and with the same water discharge introduced under low pressure. However, some air was mixed in, even then, at the very beginning of the channel. So the water surface for the flow without air was assumed to be tangent to the measured surface as shown by dotted lines in Figure 5. This correction, however, is very small and only local.

In the upper part of Figure 5, the average air concentration along the center line of the channel is plotted for the conditions (a) nozzles rejected down, and (b) nozzles rejected against the wall. All the experimental points follow a smooth curve. Using now the average air concentrations, the depth y_o as obtained from the flow of clear water, and the curves in Figure 3, one is able to predict the water surface theoretically. So computed theoretical water surface elevations are given as dotted lines in the lower graphs of Figure 5. Comparison of the theoretical water surface lines with the corresponding measured curves show good agreements outside of the pits.

For the measured water surfaces, jumps can be recognized close to the turbine pits. The reason for their occurrence was discussed before in this paper. Below the jump the measured water surface follows almost exactly the one which was theoretically computed.

The very crude theory which led to the calculated curve has served to describe the water surface very exactly if the air concentration is known. This theory must be assumed therefore to be applicable to the prototype as well, even if the distribution of average air concentration along the prototype channels cannot be predicted from the model measurements as yet.

In the measurements given in Figure 5, surface tension was reduced to 52 dynes/cm. The reason for this was to obtain a smoother water surface by giving the air bubbles, which already have broken the surface, opportunity to escape. With higher surface tension the bubbles clung to each other on the water surface and result in erroneously higher measurements for the small-scale model. For the larger scales the difference would probably be not so significant. This reduction of surface tension would not change the results as far as the bubble size is concerned for to keep

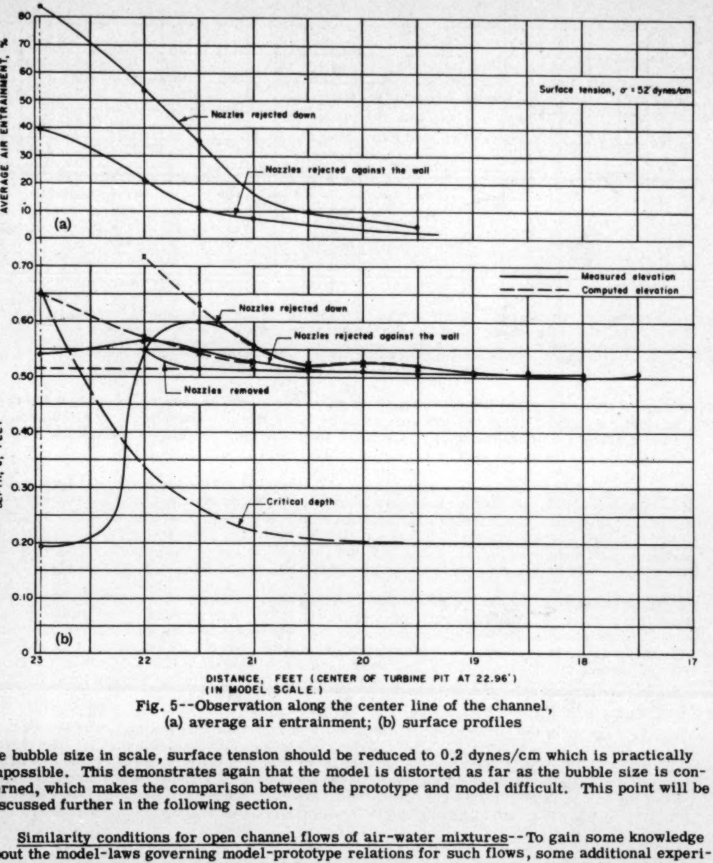

Fig. 5--Observation along the center line of the channel, (a) average air entrainment; (b) surface profiles

the bubble size in scale, surface tension should be reduced to 0.2 dynes/cm which is practically impossible. This demonstrates again that the model is distorted as far as the bubble size is concerned, which makes the comparison between the prototype and model difficult. This point will be discussed further in the following section.

Similarity conditions for open channel flows of air-water mixtures--To gain some knowledge about the model-laws governing model-prototype relations for such flows, some additional experiments were completed in a model scale 1:9 and compared with the results of the 1:20 model. The 1:9 model was built by Pelton Water Wheel Co. for the study of turbines. It represented only one turbine-pit with a section of straight discharge channel. The deflectors had not been built into this model. The wheel was arrested to approximate the condition of rejection. The air concentrations were measured at three verticals of the discharge canal (1.60, 3.67, and 7.60 ft from the center of the pit along the center line of the channel). Point measurements were made for each 0.1 foot of depth and average air concentrations found by integration over each of the three verticals. The desired tail water elevation was reached by use of a needle weir at the downstream end of the channel.

The results are plotted in Figure 6, and compared with the corresponding conditions at the 1:20 model. The linear scale (1:9 and 1:20 as indicated) was used for the distance in plotting the

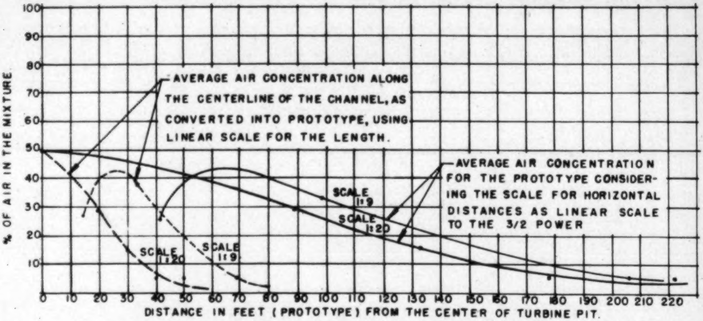

Fig. 6--Comparison of results with corresponding conditions at the models in scale 1:20 and 1:9

results as shown by dotted lines. The shape of these two curves is similar except at the very beginning of the channel. This deviation seems to be due to the creation of a strong circulation in the pit of model 1:9 where the wheel is used to deflect the flow. The curves seem to have a length scale different from those given by the linear scales of the models, however.

It appears that here Froude's model law breaks down even if it usually governs the similarity of open channel flows. It may again help to draw from the experience gathered in sediment work to find an explanation of this behavior. Sediment motion follows Froude's model law if an undistorted similarity covers not only the flow but also the sediment. This means that the sediment particles must have the same shape and size distributions in model and prototype with the absolute size of the model grains reduced from the prototype sizes according to the length scale-ratio.

A deviation from the normal similarity, usually called a distortion, is caused by some other distortion such as the neglect of some physical action in the establishment of the similarity pattern. Froude's similarity which is used in open channel flows, satisfies the condition of similarity with respect to gravity, inertia and some frictional effects. But the air entrainment depends on the internal pattern of turbulence in the flow which is probably affected to some degree by the Reynolds number and on the surface tension which determines partially the size of the individual air bubbles and their behavior in the flow and near the surface. Both the viscosity and the surface tension cannot be properly reduced to model scale such that a significant distortion exists with respect to the size and behavior of the air bubbles. The character of this distortion which is complicated by the change of bubble shapes with their size, can today not be expressed mathematically. But there appears a possibility that at least a distorted similarity exists, if the distance along the channel is reduced at a scale which equals the general length scale to the 3/2 power as seen by the comparison of the corresponding solid lines of Figure 6. However, the generalization of this rule to other problems appears to be not advisable before more evidence can be gathered to its support.

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SYMPOSIUM ON LAND EROSION[a]

INTRODUCTION

H. V. Peterson

One of the very obvious geologic phenomena that is continuously in operation throughout the Earth's land surface is erosion, the process of wearing away the soil or the surface mantle. The falling of rain drops on an unprotected slope, the flow of water across land or in a channel, the borings of a rodent, the expansion of a root, the pull of gravity, the gouging of a glacier, or the impinging of wind on an open surface are some of the forces continually at work in this erosion process. The tendency of these forces is to bring everything to a common level and the moment a point of land or a continent rises above its surroundings, gravity, rain, wind, and all the other forces set to work, bringing it back to the level of its nieghbor. The poetic expression "the everlasting hills" is an illusion, for these erosion forces have been operative since the dawn of geologic history and the evidence is conclusive that in this sequence of time numerous generations of hills and mountain ranges have been uplifted and then razed by erosion, the waste and rock debris of one range forming the source material for its successor. We could not have the great deposits of alluvium and the thick beds of conglomerate, sandstones, and shales that occur at present throughout the Earth without erosion to furnish the source material.

Considering these tremendous mountain-leveling forces that are continually active and have been since time immemorial, one might well question man's ability to influence them in any way. As an example, the sediment load carried by a single stream such as the Colorado River, which is on the order of 100,000 acre feet or 175 million cubic yards annually, dwarfs into ineffectiveness any operation that man may undertake even if he could marshal in one area all of his largest machines and initiate all of his best practices. Obviously we cannot hope to match the full forces of erosion, therefore, we must attack it on a selective basis, applying the most effective weapons at our command to areas that have the greatest value.

Erosion became a problem when man started to compete with erosion forces for the top few inches of soil on the Earth's surface. Because the growth that flourished in this soil layer was not to his liking, man, in some cases, destroyed it and planted other things more to his taste or to his profit. In other cases he liked so much that which the soil produced that he took it all and left nothing in its place. In either event he failed to realize that in these actions he had upset a long-established natural balance between erosion and the forces opposing it. Where before it had taken a thousand years to remove an inch or two of soil from a well-forested slope or a grass-covered valley, by destroying this cover or leaving only a poor substitute, he made it possible to do the same thing in a decade or even during a single storm.

So long as there were new lands to clear and subjugate, erosion was not a serious handicap to man's existence. As the productivity of old lands was destroyed by erosion, the strong moved on to new, fertile terrain, leaving the weak to subsist or perish on their abandoned acres. The succession of the rise and fall of nations throughout history can in considerable measure be attributed to this shift from old to new lands. But now that the frontiers of new lands have disappeared the strong nations of the future must be the ones that can, among other important things, successfully solve their land-erosion problems. Research in the process of erosion, the attempt to find out how and why the processes operate, where they are most destructive, and what can be done in a practical, feasible way to alleviate them is a necessary prerequisite to the solution of the erosion problem. In the Symposium to follow there are presented papers by members of the Committee on Land Erosion outlining some of the current problems and describing some of the research and study projects relating to erosion.

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[a] This Symposium was arranged for and presented at the Thirty-Fourth Annual Meeting, Washington, D. C., May 5, 1953, by Chairman H. V. Peterson of the Committee on Land Erosion, and serves as the report on the year 1952-1953 of that Committee.

The papers to be presented cover a wide range in their treatment of erosion just as erosion itself displays extreme versatility in its attack on the uplifted surface. Huberty, in his paper entitled Some Observation on Soil Erosion in the Middle and Eastern Mediterranean Area, shows that there is a sameness about the results of erosion as it affects humans in other parts of the world even though the elements involved in the process vary greatly. Loss of soil, impairment of agriculture production, impoverishment of people are the concomitants of erosion, whether they appear around the borders of the Mediterranean where civilization was cradled centuries ago or on some of our western range where use of the land was started only decades ago. His discussion emphasizes the principle now well recognized that maintenance of land, good land husbandry, and the prevention of the ravishes of erosion can be obtained only at the price of constant vigilance. A century or a few decades of neglect, or even allowing the erosion damage created during a single season or in a single storm to go unchecked, can start a chain reaction sufficient to threaten or destroy the productivity of a farm or a river drainage basin. The lesson is one that we in America need to regard with greater seriousness.

Other papers of the Symposium present a cross-section of some of the major erosion problems of the country including water and wind erosion in the Central and Great Plains states respectively, piping, a unique type of erosion prevalent on western range lands, sedimentation and erosion problems on Northwest forest lands, and finally a discussion of the impact of erosion and sedimentation on the densely populated urban areas of Southern California. The latter problem stems from the fact that a large and continually increasing segment of America's population apparently has decided to live in Southern California and in so doing they have attempted to encroach upon and pre-empt land that for eons past has been the rightful domain of mountain streams to flood over as they willed and drop their load as they wished. As these streams, on occasions, rise up in their wrath to slap down their human competitors with a slug of mud and water causing suffering and damage running into the millions, it points up the precarious nature of man's position when he attempts to ignore the forces of erosion.

The Symposium is being presented not only as a Report on the activities of the Committee on Land Erosion, but also to disclose something of what is being done in the study and treatment of erosion.

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SOME OBSERVATIONS ON SOIL EROSION IN THE MIDDLE AND EASTERN MEDITERRANEAN AREA

Martin R. Huberty

Abstract--The question is raised whether soil erosion has ever been a serious problem on the karstic formations in the Mediterranean area. Some of the soil and water conservation practices of the Romans are described, as well as the present practices and organizations in a number of countries in the middle and eastern Mediterranean region.

Soil conservationists have long pointed to the Mediterranean region as an area where man's abuse of the land has resulted in untold waste of soil resources. History records the presence of dense forests over large areas now devoid of trees, and of extensive grain fields where only shifting cultivation is now practiced. The dominant soils of this region vary from a chernozem type in southern Italy, Greece, and the coastal regions of Turkey; podzolic type soils in the mountainous regions of northern Italy and Yugoslavia, to desert soils along the eastern Mediterranean and North Africa.

Much of the hill lands of the region, which it is said were once heavily vegetated, are now practically barren with limestone rock exposures. A common belief is that wherever forests exist the soil is deep and fertile. This generalization should be questioned, for over much of the area above mentioned the parent material is a high purity limestone with a karstic structure. The soil derived from parent material of this type would be formed from the impurities in the limestone and from the organic matter contributed by the vegetation, the latter being largely dependent upon the climate. The composition of some of the limestone rock is such that it would require at least 50 cu ft of limestone to contribute two cubic feet of mineral soil. A characteristic of these limestone formations is the high degree of internal drainage (Fig. 1). Even under present sparse vegetative cover there is little or no surface runoff. Streams in the karstic regions lack the dentritic character common to those in areas with rock formation of little or no internal drainage. It would seem reasonable, therefore, to assume that there has been little overland soil erosion from the great areas of karstic limestone.

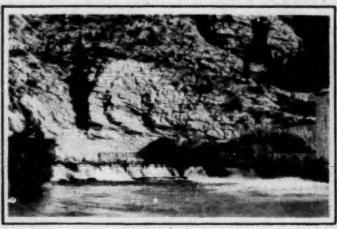

Fig. 1--Large spring on Dalmatian Coast; the stream disappears 12 kms away on other side of high karstic range

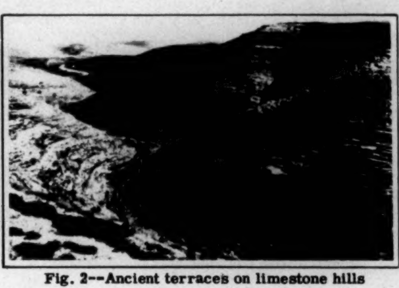

Fig. 2--Ancient terraces on limestone hills near Jerusalem, Israel

On the other hand, overland erosion of soils derived from the non-karstic rock formations has often been excessive. Within recorded time there has been much filling of bays and estuaries resulting from soil erosion.

The Romans and some of the other ancient peoples had a good understanding of soil and water conservation. Extensive ancient terraces (Fig. 2), cisterns, and water-spreading systems exist throughout northern Africa and the eastern Mediterranean areas. Flood waters were diverted from stream channels by means of low dams into contour basins rimmed with rock levees. Overflow drop structures permitted the passage of overflow from one basin to the next. As the velocities of the water in the basins were lower than those of the stream channels, deposition of sediment occurred. This practice resulted in the development of agricultural lands, replenished ground water, and reduced flood damage. Foresters, agronomists, and hydrologists who have studied Roman agriculture are of the opinion that the role of vegetative cover in reducing soil erosion and its effect upon the water regime was known to these ancient peoples.

Many of the agricultural soils of the Mediterranean area are highly permeable. Observed infiltration during storms on the volcanic soils south of Rome indicated a very high permeability, and Wayne Miles, an FAO representative in Israel, measured infiltration at rates in excess of four inches in fifteen minutes on a medium textured soil. Runoff is often accentuated, however, by cultural practices and surface drainage systems. In Italy in particular, surface drains are often installed parallel to the steepest slope rather than on a moderate grade. This results in much soil erosion. The farmers, however, consider the damage resulting from poor drainage to be greater than those resulting from erosion. Contour drains would probably provide adequate drainage and also conserve soil.

Gino Passerini is head of a small soil conservation group that is doing very effective work in Italy. Much of his organization's work is done on rough terrain in the control of mountain torrents and reduction of erosion from "bad lands." The Italians have developed a technique for the treatment of these badly eroded clayey soils. It consists of dynamiting the leading edges of the ridges and then planting trees, usually pines or forage crops, on the filled area. High hopes are held for this method of reclamation. It does look to be expensive, however.

The Israel government has an active conservation service. Nathan Gil, its Director, spent time in the United States studying the organization and work of the U. S. Soil Conservation Service. The program of his organization includes contour farming, crop rotation, farm reservoir building, water spreading, and reforestation, and extends from the Lebanon border south into the rolling, wind-blown soils of the Negev. It is a costly program that only high benefits will justify.

As mentioned previously the soil of north Africa are classed as being of desert type. The governments of Tunis and Algeria, (and the Italian government during the period it controlled the territory of Libya) recognize the soil-erosion problem and have done a great deal to reduce erosion. One phase of the work that received much attention in Libya was the attempt to control sand blowing through the use of low wind breaks made of short dead plants. At times whole sections of sand dunes were covered with these low barriers each of which might encompass an area of not more than 100 sq ft. These breaks are apparently long lived and are very effective in stabilizing the soil. The second stage of the stabilization program consists of planting acacia and other drought resistant shrubs within the small compound provided by the twig barrier.

Sand dunes are usually considered to be worthless waste land. Actually they can often be of very great economic value. In arid regions where rainfall is low, but often of high intensity, the dunes serve as rain interceptors and thereby aid in the recharge of the subterranean aquifers.

The high plains lands of Libya immediately inland south from the Mediterranean Sea normally receive sufficient rainfall to produce a short grass cover, or under farming, a moderate grain crop. Over the years this land has been overgrazed, resulting in heavy erosion and a loss of soil water storage capacity. Soil erosion on the plains (gefara), while objectionable, does not cause serious economic loss.

The aggressive approach to soil conservation often fails to recognize the benefits that accrue from erosion. Erosion has built the deep alluvial valley fills on which much of the world's crops are produced. For example, it filled in the low lying area known as the Pontine Marshes to such an extent that some 140,000 acres of land could be reclaimed and become highly productive.

While we presently are giving much attention to the very important problem of soil erosion we must not lose sight of the fact that much was known about this problem by ancient peoples. Wars, droughts, rainfall of high intensity, attitudes, and economic conditions have and will continue to be among the important factors which determine land use and land abuse.

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WATER EROSION PROBLEMS AND CONTROL ON NON-IRRIGATED AGRICULTURAL LANDS

Louis M. Glymph, Jr.

Abstract--The principal types of water erosion on non-irrigated agricultural lands are described. A generalized soil erosion map indicating extent and degree of erosion is presented. Selected summary data on rates of soil loss from 0.01-acre plots in grasses, continuous row crops, and adapted crop rotations are given from nine experiment stations in important farming areas. Factors influencing rates of erosion are enumerated and discussed briefly. The objective of erosion control on agricultural lands is specified and some of the methods and principles of erosion control are listed.

Introduction--The principal types of water erosion affecting agricultural lands are (1) sheet erosion, (2) rill erosion, (3) gully erosion, and (4) stream channel erosion.

Sheet erosion refers to the more or less uniform removal of soil from an area without the development of conspicuous channels. The numerous, small, discontinuous channels which facilitate the process are not readily discernible and are easily obliterated by tillage. Although sheet erosion is often unobserved, it may be evidenced by the appearance of lighter colored soils in cultivated fields and by the accumulation of freshly eroded material at the foot of slopes.

Rill erosion refers to the removal of soil by the cutting of numerous small but conspicuous water channels. Such channels can also be obliterated by plowing and tillage practices but soils may be gradually truncated and the land slopes shortened through their frequent recurrence and effacement. Sheet erosion and rill erosion are commonly considered as a single phase insofar as control is concerned.

Gully erosion is the removal of soil by concentrated flow of water with resulting formation of channels that cannot be crossed by ordinary tillage implements. The size and shape of gullies depends upon numerous factors, including nature of soils and parent material, size of drainage area, climatic environment, and age.

Stream channel erosion refers to the enlargement of stream channels or entrenched watercourses by deepening and widening as a result of flowing water.

Extent of soil erosion--The first three of these erosion types commonly occur as concomitant processes and many eroded or eroding areas are simultaneously affected by all three of them. In some parts of the country, particularly in the Great Plains and sub-humid regions, much of the land is also affected by wind erosion in conjunction with one or more of the water erosion types. Most of the land area of the country has been affected by erosion in one or more of its various forms.

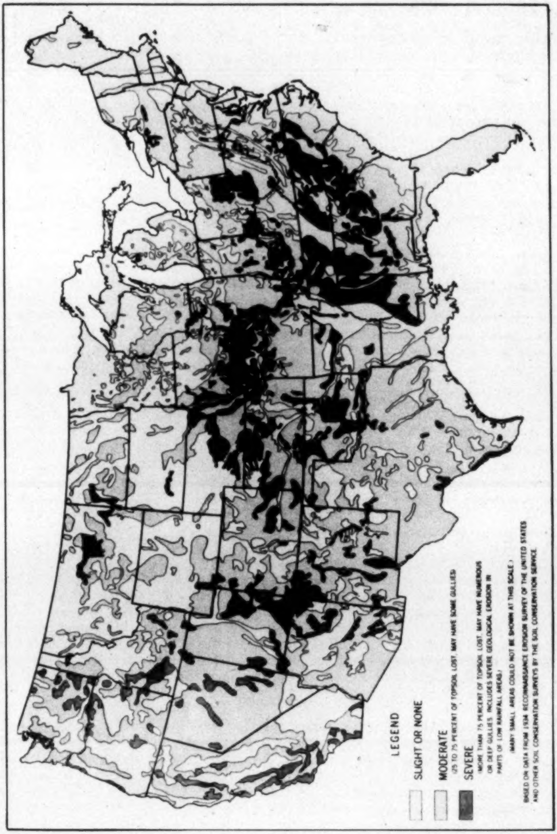
LEGEND
SLIGHT OR NONE
MODERATE
(25 TO 75 PERCENT OF TOPSOIL LOST, MAY HAVE SOME GULLIES)
SEVERE
(MORE THAN 75 PERCENT OF TOPSOIL LOST, MAY HAVE NUMEROUS OR DEEP GULLIES. INCLUDES SEVERE GEOLOGICAL EROSION IN PARTS OF LOW RAINFALL AREAS.)
(MANY SMALL AREAS COULD NOT BE SHOWN AT THIS SCALE.)
BASED ON DATA FROM 1934 RECONNAISSANCE EROSION SURVEY OF THE UNITED STATES AND OTHER SOIL CONSERVATION SURVEYS BY THE SOIL CONSERVATION SERVICE.

Fig. 3--Generalized soil erosion in the United States

The extent and degree of historic erosion are indicated by a generalized soil erosion map which has been prepared by the Soil Conservation Service, Figure 3. The data from which the map was compiled indicate that erosion has been severe on about 14 pct of the land area; that a moderate amount has occurred on about 47 pct of the area; and that about 39 pct of the continental land area has been affected slightly or not at all by erosion.

It should be emphasized that the preceding estimates of the extent and severity of erosion, and as reflected by Figure 3, refer to past erosion and not to the current erosion rates. Abnormally high rates of erosion occur in all of the states under certain circumstances. Without exception each state has some land on which both the extent and rate of water erosion is a matter of primary importance from an agricultural standpoint.

Rates of soil erosion--The effects of land utilization upon rates of sheet erosion have been well documented by the measurement of soil loss from plots and fields under a variety of use and cover conditions. Observations have been made and data obtained in practically all of the major farming areas of the country. One of the overwhelming conclusions from such studies is that development and utilization of the land for agricultural purposes has caused a tremendous increase in the rate of erosion. Probably most of the extensive area of severe erosion in the country today has resulted from breaking of natural sod covers, clearing of forest and woodlands, and grazing of range and wooded areas, with only limited attention being given to conservation of the soil resource.

The data showing effects of land use and cropping systems upon the rates of sheet erosion are too numerous to present in a brief discussion. The relationships are well illustrated, however, by measurements made at the Conservation Experiment Station at Bethany, Missouri, for the ten-year period 1931-1940 [SMITH and Others, 1945].

At the Bethany Station, ten adjacent one-hundredth acre plots, each 6 × 72.6 ft in size, were established on an eight per cent slope of Shelby loam soil. Soil and water losses from these plots were measured for different land uses. It was found that the average soil loss from a plot in bluegrass sod was 0.16 ton per acre annually as compared with 50.93 tons per acre annually from land in continuous corn planted up and down the slope. Other adjacent and similar plots in a three-year rotation of corn-wheat-hay, during the same period, lost 9.06 tons of soil annually. At these rates of soil loss, the time required to erode one inch of soil from the plot in continuous corn was about 3.5 years, from the rotation plots about 20 years, and from the plot in bluegrass sod about 1100 years.

Data on soil loss from plots for selected land use and cropping systems in some important farming areas are shown by Table 1. The tabulation, however, is by no means a complete and comprehensive summary. Much additional information of this nature is available from most of the State Agricultural Experiment Stations and from numerous other sources.

From the mass of data available, it seems safe to conclude that the practice of agriculture is not only affected by erosion but is one of the primary reasons for an acceleration of erosion rates above those of normal geological processes.

The Soil Conservation Service has engaged in extensive studies to interpret results from the experimental areas in terms of the rates at which the agricultural lands of the country are being damaged by accelerated erosion. One comprehensive study of rates of decline in productivity of the soil resource gave consideration to the combined effects of several factors, including the accumulation of toxic salts in soils under irrigation, rising water tables in drained and irrigated lands, depletion of water supply for irrigation, as well as the effects of erosion. For a summary of this study the agricultural lands were classified on the basis of time required for the several deterioration factors to cause permanent damage to the land. Erosion was by far the dominant cause of permanent land damage in most parts of the country.

As defined for the study, permanent damage resulted when cumulative erosion caused either a change in recommended land use or necessitated more intensive treatment for erosion control. Damage occurring at a rate sufficiently rapid to cause permanent impairment of land within 15 years was classified as "critical." That causing permanent impairment within 15 to 30 years was classified as "serious"; and that in a period of time longer than 30 years as "slowly deteriorating." Upon this basis of classification about 25 pct of the cropland in 1945 was being damaged at a critical rate; about 27 pct at a serious rate; and about 48 pct was slowly deteriorating (see Table 2).

Table 1--Average annual soil loss from one-hundredth acre plots at various localities

Location	Soil type	Land slope	Period of record		Average annual rainfall	Land use and cropping system[a]	Average annual soil loss	Reference
			Dates	No. of years				
		pct			inch		tons/acre	
Pullman, Wash.	Palouse silt loam	30	1932-42	10	20.78	Perennial grasses	0.08	HORNER and Others [1944]
						Bare, untilled	22.08	
Temple, Tex.	Austin clay	4	1931-41	11	32.74	Bermuda grass	0.02	HILL and Others [1944]
						Continuous corn	20.58	
						C-O-Co[a]	12.95	
Tyler, Tex.	Kirvin fine sandy loam	8.75	1931-40	10	40.66	Bluegrass	0.08	POPE and Others [1946]
				10		Continuous cotton	24.07	
			1931-35	5		Co-C-L	17.97	
			1936-40	5		Co-Sg-Cp	16.19	
Guthrie, Okla.	Stephensville fine sandy loam	7.7	1930-38	9	30.63	Bermuda grass	0.02	DANIEL and Others [1943]
						Continuous cotton	18.9	
						W-S-Co	4.2	
Clarinda, Iowa	Marshall silt loam	9	1933-42	10	28.87	Bluegrass	0.03	BROWNING and Others [1948]
						Continuous corn	38.3	
						C-O-Cl	11.3	
Bethany, Mo.	Shelby loam	8	1931-40	10	29.49	Bluegrass	0.16	SMITH and Others [1945]
						Continuous corn	50.93	
						C-W-H	9.06	
La Crosse, Wis.	Fayette silt loam	16	1933-38	6	33.81	Bluegrass	0.10	HAYS and Others [1949]
						Continuous corn	111.7	
						C-B-Cl	27.8	
Zanesville, Ohio	Muskingum silt loam	12	1934-42	9	38.91	Bluegrass	0.023	BORST and Others [1945]
						Continuous corn	99.3	
						C-W-H-H	13.4	
Statesville, N. C.	Cecil sandy clay loam	10	1931-38	8	47.80	Mixed grass	0.31	CORLEY and Others [1944]
						Continuous cotton	31.22	
						Co-C-W-L	14.28	

[a] Crop rotation symbols: C = corn; O = oats; Co = cotton; W = wheat; H = hay; S = sweetclover; Cl = clover; B = barley; L = lespedeza; Sg = sorghum; Cp = cowpeas.

Table 2--Rates of land damages in the United States[a]

(primarily by soil erosion)

Rates of land damage	Approximate area[b]	
	Land in farms	Cropland
	million acres	million acres
Critical	256	113.8
Serious	279	120.3
Slowly deteriorating	607	216.6
Total	1142	450.7

[a] From files of the Soil Conservation Service.
[b] Adjusted to 1945 U. S. Census data.

Factors involved in erosion--The primary factors influencing rates of erosion on non-irrigated agricultural lands are: (1) climate, especially the amount, frequency, duration, and intensity of rainfall; (2) inherent erodibility of soils; (3) vegetal cover - kind, density, and seasonal occurrence; (4) topography, including the length and degree of land slope; (5) cropping and tillage system; and (6) erosion control practices.

It is apparent that soil erosion is the resultant action of many interrelated factors. Some of the factors involved are natural forces which cannot be modified by man. Others can be modified but little, while some of the important factors can be modified, changed, or adjusted in important details with resulting important effects upon the nature and rate of erosion.

Recent experiences with rain-making suggest that it may be possible to modify the occurrence of rainfall, which, of course, is the primary factor responsible for water erosion. At the present time, however, precipitation amounts, rates, and seasonal distribution are natural factors not subject to consistent regulation. But the effects of rainfall upon erosion can be ameliorated greatly in most areas by the adoption of grazing practices, cropping systems, and tillage methods designed to provide a maximum amount of protective vegetative cover on the soil during the seasons of erosion-producing rains.

The erodibility of soils is one of the factors which is subject to change. In general, soils with high fertility, granulated open structure, and a good supply of organic matter are among those less susceptible to erosion. Soil structure, organic matter, porosity, fertility, and other characteristics affecting rates of erosion may be influenced greatly by the use and treatment of the soil.

Vegetative covers such as grasses, growing crops, tree and shrub canopies, surface residues, or humus layers, aside from rainfall, probably have the greatest influence upon the rate of erosion. The nature and distribution of vegetative covers, and consequently their effects upon erosion, are subject to modification in many ways by man's activity. The use of vegetation as a means of erosion control under certain conditions has long been an established practice.

The length and degree of land slope are the more important topographic features from the standpoint of erosion on agricultural lands. Where other factors are equal, rates of sheet erosion increase with increasing steepness and length of slope. The length of slope can be effectively and economically shortened by terraces or dikes built across the slope to intercept surface runoff, with consequent reduction in erosion rates.

Overgrazing, sustained production of clean-tilled crops, and improper disposal of runoff water from agricultural lands have been important factors in the development of gully erosion. In some localities accelerated rates of gully erosion can be traced to changes in stream regimen because of the straightening and enlargement of stream channels for drainage improvements, flood control, and similar purposes. In other areas, particularly the arid and semi-arid southwest, there is evidence that changes in climatic environment may have been an important factor in acceleration of gully erosion rates.

Erosion control--Maintenance and improvement of the soil resource for the production of agricultural products is the primary objective of erosion control practices on agricultural lands.

Proper land use is a basic requirement for the accomplishment of this objective. Some soils can not be farmed intensively without excessive erosion damage, because of shallow depths, steepness of slopes, or other limiting characteristics. Under good management of protective vegetative covers, however, these same soils may be used for grass or timber production without being damaged by erosion. Adaptation of soils to uses which minimize the erosion hazard is the first step toward successful erosion control on farmlands.

The effects of soil-conserving crop rotations as a means of erosion control on land adapted for crops has already been pointed out. The length of desirable crop rotations, the crops included and their sequence in the rotation, depend upon the soil and rainfall characteristics, and the length and degree of land slopes. Cropping systems alone, however, can seldom provide the degree of erosion control required for preservation and improvement of the soil. Other measures such as crop residue management, tillage practices, strip cropping, contour cultivation, fertility amendments, waterways and outlets for disposal of runoff, and terraces are necessary in addition to cropping systems.

The control of sheet erosion on range and pasture lands depends primarily upon the type and density of protective vegetative covers. In addition to reseeding in some areas, the primary erosion control practices are fencing, the regulation of grazing, and the development of an adequate and well-distributed water supply. Fire control, selective harvest, and other management practices are essential for stabilization of sheet erosion on farm, forest, and woodland areas.

To some extent, control of gully erosion can be accomplished as a result of the measures applied for control of erosion in the area tributary to the gullies. Many gullies, however, require special treatment for their stabilization. Combinations of vegetative measures and structures may be required, depending upon the size, nature, and cause of the gullies. In some localities stabilization of deeply entrenched gullies and stream channels is necessary for the successful establishment of measures and practices required for control of sheet erosion.

Conclusions--It seems reasonable to conclude that much knowledge and information have been accumulated which aid in a better understanding of the causes, processes, and control of water erosion on agricultural lands. It is recognized that much additional information is needed to better define the relationships of cause and effect in quantitative terms, as a stimulus for further development and refinement of means and measures for erosion control. Past research and accumulated field experience have provided many effective and beneficial soil conservation methods. There needs to be a wider application of currently accepted practices for erosion prevention and soil improvement.

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THE WIND EROSION PROBLEM IN THE GREAT PLAINS

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(Contribution No. 488, Department of Agronomy, Kansas Agricultural Experiment Station, Manhattan, Kansas, and the Bureau of Plant Industry, Soils, and Agricultural Engineering, U. S. Department of Agriculture. Cooperative investigations in the mechanics of wind erosion.)

Abstract--This is a review paper summarizing briefly current knowledge and philosophies relative to the wind erosion problem in the Great Plains area of the United States. The principal types of wind erosion experienced by the area are identified as "selective erosion" and "mass removal." Present and historical aspects of the problem are outlined. An equation expressing the regimen of soil removed by wind tunnel tests for variations of vegetative cover on soils of different structure and surface roughness is presented. Climatic variation and chance occurrence of adverse combinations of climatic factors are cited as fundamental to the problem. The principles involved and methods used for abatement of the problem are discussed. The needs for climatic, soil, crop, tillage, and erosion control practice research for the development of adequate wind erosion control measures or practices are cited.

The accelerated erosion of soil by wind in the Great Plains is a problem associated with land use. The climax vegetation of the area was predominantly mixed and short grasses. Under grass, the soils were relatively stable and organic matter accumulated throughout the upper portion of the root zone. The equilibrium between vegetation, soils, and climatic environment has been disturbed by use of the lands for annual cultivated crops. Instability of unprotected soil to the forces of wind is the item of major concern with respect to erosion.

Principal types of wind erosion

Little consideration has been given to classifying types of wind erosion although several forms and processes have been identified by FREE [1911], BAGNOLD [1943], and CHEPIL [1943]. There are, however, two distinct types of phenomena in the Plains.

The first of these is "mass removal" of the soil materials from a land surface. It is associated with the finer textured silt and clay soils. In these soils, all of the primary particles may be suspended and removed by wind. They are usually loessial in origin. While the basic soil particles may be aggregated, little sorting of basic materials occurs from wind action. In general, the saltation movement of aggregates causes their breakdown and the soil materials may be transported far from the source area. In the Great Plains these soils are usually dark in color and are known as the "hardlands."

The second type of wind erosion may be termed "selective erosion." It is the sorting of relatively fine materials from an eroding surface. The phenomenon is common to sandy lands containing some basic soil materials too large to be suspended by the wind and removed from the source area. Selective erosion results in the loss of the more fertile portions of the soil from the eroding area. Local products are the accumulation of sand into hummocks or dunes. In some cases extremely coarse material remains in place to form a desert pavement. The soils are usually residual or formed from mountain outwash.

Areal extent

The wind erosion problem in the Great Plains is present in portions of a ten-state region. For convenience the five-state area of Montana, North Dakota, Wyoming, South Dakota, and Nebraska are often called the Northern Plains. Spring wheat is the principal crop of these northern states. Colorado, Kansas, New Mexico, Oklahoma, and Texas form a group called the Southern Plains. Winter wheat, sorghum, and cotton are the principal crops of this area.

Clear cut lines to delineate the areal extent of the problem cannot be drawn. As an estimate, approximately 25 pct of the total ten-state area, or 250,000 sq mi, are subject to the wind-erosion hazard at recurring intervals in a moderate to severe degree. Almost every year the problem will be severe in some more or less localized portion of one or several states. This should be regarded as a condition normal to the area. It is no more unusual than, say, a flood on one of the many secondary streams of the Mississippi River system in a given year. Such conditions are not a harbinger of wide-spread disaster conditions, although they are often misjudged as such.

Upon occasion, climatic conditions may cause severe wind erosion over large areas in several states, although the probability of experiencing such an event is low. This is the condition that prevailed in the 1930's.

Historical aspects of the wind erosion problem

Prairie fires are known to have been common to the ecological development of Plains grasslands. Grazing by buffalo, drought, and the activities of the Indian undoubtedly caused periodic deterioration of the range and it seems reasonable to assume that erosion of soil and plant material by wind existed before white settlement.

White settlement of the Plains west of the Missouri River occurred an even century ago. A report on dust storms during the period 1850-1900 has been given by MILAN [1946]. An excerpt from the newspaper Kansas Free State at Lawrence, Kansas in 1855 is as follows: "The strong south winds that we experience here are our greatest annoyance. They frequently last for several days, and are loaded with the black dust from the burnt prairie, which penetrates every corner of our houses, and makes everyone who is exposed to it as sooty as a collier. This annoyance, however, will not be so great when the surrounding country is brought under cultivation, and the prairies cease to be burned." A century later we have reached the cultivated state that appears to have been the goal a century ago. Today the winds carry little of the residue from prairie fires; their burden is the soil itself.

Much has been written about the folly of breaking the sod of the Plains. The fact of the matter is that cultivation of deep lands in rainfall belts of 16 to 18 inches or more offers no greater an overall erosion hazard than exists in most humid areas. The phenomenon is different in nature, and erosion of soil in the form of a "black blizzard" is simply more spectacular than muddy water.

Toward the western side of the Plains in rainfall belts of 16 inches or less a serious erosion problem exists on shallow soils. The Soil Conservation Service classifies many of these as Class IV lands. These lands are transitional between those suited for cultivation and those that should not be plowed.

During and following World War II a large acreage of sod lands were placed under cultivation. The plow-up for 1948 was in excess of 1.4 million acres. During the same year 0.7 million acres were retired from cultivation. The net increase in cultivated acres from 1944 is shown in Figure 4. This figure is based on compilations of data by the Conditions Committee of the Great Plains Agricultural Council. FINNELL [1949] found that almost one-half of the newly plowed lands in the Southern Plains was Class IV and one-fourth was unsuited entirely for cropland. The retirement of land from cultivation has exceeded new plow-up since 1949. In general, the climatic hazards of drought and high winds have been at a low ebb during the past decade. It will be fortunate in the extreme if further retirement of hazardous lands is made before a climatic situation causes them to go out of control.

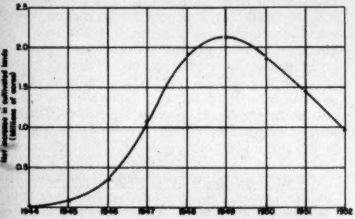

Fig. 4--Net increase in cultivated lands in the Great Plains over those cultivated in 1944

Chief factors involved in erosion

Precipitation, temperature, the level of wind movement, and land use are interrelated to comprise the wind erosion hazard on a given soil. The characteristics of each vary with time and season at a given location.

Land use--Use of land in the Plains seems quite simple in that it may be classified as range or cultivated land. The vicissitudes of weather are such, however, as to require a science of range management on grasslands. The cultivated lands are, in general, cropped to wheat, sorghum, or cotton with fallow periods designed to augment soil moisture. On cultivated lands it is very difficult to follow a routine system of management and cropping due to large variations in climate. The tendency is to employ flexible systems to utilize fully the soil-moisture supply on hand. There is a good deal of danger in this practice, particularly on the poorer soils. For example, one often hears the view expressed that Class IV lands can be cropped for a few years when moisture is plentiful and then retired to grass. Just how these lands can be returned to a protective grass cover before a non-determinable drought period is not known. Again, legumes or grasses are not employed generally in cropping sequences on drylands in the High Plains. A U. S. HOUSE DOCUMENT [1949] gives an estimate that their use is needed on 30-million acres in the Missouri Basin alone.

Farm machinery and its operation is an integral part of land use. The array of different-type plows, sweeps, chisels, subsoilers, disks, and drills all attest to the struggle toward improved crop management and soil and moisture conservation in the Plains area.

Soils and their properties--The Chernozem, Chestnut, Reddish Chestnut, and the Brown soils predominate in the Plains. A lime accumulation layer is characteristic of nearly all soils of these four groups. Because of limited amounts of leaching below the zone of root development, the soils are quite fertile. In general, the soils are formed from Rocky Mountain outwash and many of them have a loessial covering.

Soil texture and structure appear to be the most important soil properties with respect to erodibility of the soil by wind action. Studies by CHEPIL [1953a] have demonstrated that the dry clod structure of soils is related to their texture. The most stable structure is normally found on soils containing 25 to 30 pct clay. Very sandy soils and those containing large amounts of clay are the most erodible basically. The unigranular nature of the sands inhibits the formation of stable dry clods, while excessive amounts of clay tend to cause the formation of a large proportion of water-stable aggregates. The aggregates are, however, normally of a size and apparent density that are moved easily by wind.

In researches on the mechanics of wind erosion, CHEPIL [1953b] found that the per cent by weight of soil material <0.42 or <0.84 mm in diameter in the surface inch of soil bears a relationship to the erodibility of soils by wind. Values of the percentage as determined by the sieving of soils in a dry state afford a convenient index of their erodibility.

Vegetal cover--Vegetal cover tends to vary with precipitation, soil texture, and depth. Thus, as we proceed from east to west across the Plains the amount of vegetal cover produced and the crop residues available for soil protection become less. The close association between wind erodibility, soil texture, the percentage by weight of erodible soil material <0.42 mm in diameter at the surface and the weight of surface residues found in a field study by ZINGG and Others [1953] in eastern New Mexico in the spring of 1952 is demonstrated by the average results shown in Table 3.

Table 3--Data on surface residues and soil removal

Soil textural group	Dry surface soil material <0.42 mm in diameter	Weight of surface residue	Measured soil removal[a]
	pct	lbs/acre	tons/acre
Loamy	69	875	2
Sandy	77	560	9
Very sandy	92	400	67

[a] Weight of soil material removed by a portable wind tunnel at a surface drag level equivalent to 3000 pounds per acre.

Surface roughness--The roughness of a field surface governs to a large extent the distribution of wind force on it. The roughness may be in the form of soil clods, ridges, or residue orientation. Roughness tends to limit the movement of erodible soil material and to concentrate the wind force on relatively stable surface projections or vegetal residues. In the evaluation of field surfaces, a height parameter called the "ridge roughness equivalent" has been developed by ZINGG and WOODRUFF [1951] to gage this factor.

Relationships of soil eroded by wind to surface factors--In considering field surfaces the factors of dry clod structure, weight of surface residue, and surface roughness have been used in combination to account for a portion of measured wind erodibility. For example, an empirical relationship developed from portable wind tunnel tests by ZINGG and Others [1953] of a group of fields in New Mexico is

$$\log x = -8.96957 + 7.33294 \log A - 1.17067 \log RK$$

where x is the soil material eroded from the test surface in tons per acre, A is the percentage of dry surface soil material <0.42 mm in diameter, R is the weight of surface residue in pounds per acre, and K is the ridge roughness equivalent of the surface in inches. The correlation of the expression is 0.834, which means that approximately 70 pct of the variability of soil eroded is accounted for by the measured variables. The equation was developed for an average surface wind drag equivalent to 3000 lb/ac.

Climatic factors--Wind movement, humidity, precipitation, and temperature must be considered to interpret the wind-erosion problem in the Plains. Normally, the period of most intense wind movement occurs in February, March, and April, prior to the seasonal fall of precipitation in the summer months beginning in May. In the normal course of events, soil structure of a wind-stable type tends to break down over the winter period. A dry, granular surface-soil condition is usually present during the period of high winds which comes in the form of storms with the seasonal change from winter to spring. Unfortunately, a majority of the windstorms occur before the seasonal period for new vegetal growth. Thus, in large measure, the wind-erosion problem is a seasonal one and priority must be given to crop and land management methods and practices which will yield control in the late winter and early spring.

Irregular cyclic variations in wind movement, precipitation, temperature, and resulting crop growth over periods of years are also characteristic of Plains climate and agriculture. High winds and temperatures tend to be inversely related to precipitation and vegetal growth. Hence, during adverse periods of climate all factors combine to produce conditions favorable to soil movement by wind. Studies of these several factors and a speculative approach to the problem have been reported by ZINGG [1953]. Suffice to say that the factors of climate were extremely adverse in the 1930's and have been more favorable than average during the last decade. Further, cyclic fluctuations of this nature are to be expected. Levels of wind movement are also amenable to study on an intensity-frequency basis as shown by ZINGG [1950]. Thus, many of the techniques employed in hydrology may be used in evaluating the wind erosion phenomenon from a climatic standpoint.

Corrective measures for abating wind erosion

Decreasing force of wind on soil--Under climax conditions prairie grasses, wild legumes, forbs, and shrubs possibly afforded the maximum protection of the soil surface from wind. Land-use experience indicates that range use with proper management is the maximum capability of the shallow lands where moisture is the limiting factor in plant growth.

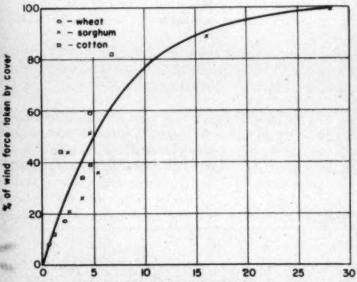

Fig. 5--Per cent of wind force taken by cover in relation to RK

Retaining a maximum cover with crops and their residues approaches conditions for good protection most closely on cultivated lands. The use of the combine where only the grain is removed from the field was a revolutionary step in the harvesting of wheat and grain sorghum. Retaining a portion of crop residue on the surface under both fallow and continuous cropping sequences followed shortly, and management methods to accomplish this end are still in their infancy. The delayed fallow in which wheat stubble is not worked in dry years until after spring winds is a further advance. All these techniques are in the direction of employing methods which approximate the protection afforded by the native vegetation.

The ability of crop residues to remove the direct force of the wind from the soil is illustrated in Figure 5. In this case the product of the weight of surface residue and a parameter of surface roughness are plotted against the percentage of wind force taken by the cover at a height greater than one inch above the average elevation of the soil surface. The values were calculated from dimensionless velocity profiles obtained in field wind tunnel studies by a technique described by ZINGG and Others [1952]. The value of R is the weight of surface residue in pounds per acre and K is the ridge roughness equivalent of the surface in inches.

The planting of crops in a row direction perpendicular to prevailing high intensity winds is a device designed to increase the efficiency of vegetal protection to the soil. The employment of alternate strips provides further mechanical protection through their barrier effect and the elimination of contiguous erodible areas. Unfortunately, in some areas of the Plains almost equal numbers of damaging winds come from east-west and north-south directions. In portions of the Northern Plains benefits are derived from plantings and establishing strips in a north-south direction. In portions of the Southern Plains the east-west directional planting yields benefits.

Field windbreaks afford mechanical protection of the barrier type and are adapted to deep soils having an ample supply of moisture to support them. Their employment to form a part of the land pattern in adapted areas is a development which will come with time. For example, plantings are going forward steadily in portions of southwestern Oklahoma and adjoining areas of Texas. The development is in the form of a network in both north-south and east-west directions.

Enhancing vegetal cover--Management techniques which yield a maximum of soil stability and conserve and utilize moisture efficiently for plant growth are necessary for sustained land use in the Plains area.

Marked developments in higher-yielding and more drought resistant varieties of crops have been and are being made. The introduction of improved varieties of grain sorghum are a boon to the Southern Plains. The average water requirement of sorghum in Colorado was determined by BRIGGS and SHANTZ [1914] to be 322 pounds per pound of above-ground dry matter production. A comparable value for wheat was 481. Not only is the sorghum plant more efficient in the use of moisture but it is a crop which can be planted following winter wheat failure.

The organic carbon and nitrogen content of dryland soils has been decreasing under dryland cultivations. During a 30-year period of cropping at Hays, Kansas, MYERS and Others [1943] found the decrease was approximately one-third from the original level. During the past 30 years the development of improved crops has tended to offset yield declines due to lowering fertility. At the present time many field trials are underway to evaluate the effects of fertilizer on dryland soils. It is reasonable to assume that enchanced crop growth, efficiency of moisture use, and increased soil protection will be forthcoming in years when moisture is not the limiting factor in crop growth. In the higher rainfall areas of the Plains leguminous crops are being employed in increasing amounts with beneficial effects to soil condition and subsequent crop growth.

Maintaining protective cover on the land once it is grown is not the least of the problems of dryland agriculture and wind erosion control. Under drought conditions, pressures to utilize residues by livestock grazing or harvesting for forage are great. Maintaining a supply of forage on hand sufficient to carry livestock through drought years is fundamental to solving the problem. Some progress has been made in storing silage but, in general, the supplies are very inadequate.

Tillage and emergency control methods--In addition to implements designed to leave residues on the soil surface, machines capable of penetrating the soil to considerable depth are being employed. Some of the processes are deep chiseling and plowing, subsoiling, and listing.

The objectives of deep chiseling and subsoiling are to loosen relatively impermeable or consolidated soil materials below the depth cultivated normally to provide more favorable conditions for moisture penetration and root growth. Again, by using the chisel or the lister it is possible to bring consolidated cloddy soil material to the surface to provide relatively wind stable soil conditions for some period of time. An illustration is the employment of the lister in the growing of cotton in the Southern Plains. The soils are blank listed late in the winter months just prior to the season of high winds. After the season of high winds the lands are again listed in the cotton planting operation.

Deep plowing to depths of 12 to 18 inches also has become a common practice on sandy soils on the Southern Plains. Following the sorting action of wind erosion many of the soils have an extremely sandy surface. In general, they are underlain with finer textured material and immediate benefits are associated with burying the erodible surface material and bringing a less erodible soil to the surface. Unless the practice is used as an aid to the establishment of relatively stable land use systems it is exploitative in nature. To date the development is largely of the exploitative variety. The process cannot be repeated many times without accumulating a deep mantle of erodible sand material which will offer a much greater wind erosion problem than exists currently.

Emergency tillage to control erodible land surfaces is more or less a last resort measure to keep land from going out of control or to minimize the abrading action of saltating soil grains on young plants. It is a temporary expedient but under certain conditions is capable of yielding great benefits and saving a crop. The object is to limit soil movement by roughening portions of a field to the point where they are nonerodible or will trap the soil materials moving from intervening areas. Usually from ten to 50 pct of a field is worked at one time in alternate strips. The practice is carried out best with chisels of approximately four-inch width at spacings of two feet. Its success is dependent upon timeliness of the operation and bringing stable clods to the surface. In the state of Kansas the county boards of supervisors have legal authority to enforce the emergency tillage of land to eliminate the hazard to adjoining farm lands.

Moisture conservation practices--The practices of terracing and contour farming are developing well in eastern sections of the Plains where both wind and water erosion occur. Their function is a dual one of moisture conservation and erosion control. Again, deep chiseling and subsoiling has as its partial goal the conservation of moisture although little factual information is available on the subject.

The practice of using rod weeders and packers in seed bed preparation is usually thought to decrease evaporation losses but, again, information of a factual type is meager or non-existent.

Wind-barrier effects obtained from windbreak placement, strip cropping, and row direction practices should be accompanied by modified evaporation phenomenon. In general, however, possible effects have been considerations of a refined nature in relation to the numerous aspects of Plains agriculture.

It has been demonstrated by DULEY and RUSSELL [1939] that stubble-mulch systems of farming cause increased infiltration of water into soils. Studies to evaluate their influence on evaporation and plant growth are underway at a few locations.

In general, it may be stated that less is known concerning soil moisture conditions associated with various practices and land management than any other phase of the dryland problem.

Research needed for development of adequate abatement measures

Climatic, soil, crop, tillage, and erosion control practice research is needed for the development of adequate control methods. Many of the factors comprising the problem are interdependent. Thus, the nature of winds, precipitation, evaporation, soil properties and moisture, plant growth and cultural techniques are involved. One of the greatest needs is for the development of new research techniques employing cooperation of men trained in various fields of physical and biological science.

The characteristics of wind movement need much more study from the erosion standpoint. The motivating force in the problem is wind and the scale and degree of atmospheric turbulence as well as velocity and duration are important. Climatological research should be carried out as an integral part of studies dealing with soil, water, and plant phases of the problem and its control. Again the characteristics of wind as it passes over barriers and land surfaces of different roughness and its force distribution on such surfaces is little understood.

One of the major methods of control on cultivated lands is the maintenance of adequate vegetal cover to protect a given soil from the wind forces anticipated. In most cases this requires the growing of maximum cover. In general, better utilization of precipitation for plant growth is prerequisite. Hence, methods of increasing infiltration, decreasing surface runoff and evaporation, and the adoption of crops and systems of crop culture and tillage that are efficient in the use and conservation of moisture should be the objectives of intensified research.

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DISCUSSION

Louis M. Glymph, Jr., (Agriculture Research Service, Lincoln, Nebraska)--Erosion by wind is shown to be the resultant of numerous variables, many of which are interdependent. Aside from wind itself, vegetative cover seems to be the principal factor in defining the susceptibility of soil to wind erosion. Maintenance of a protective vegetative cover on the soil during the season of most intensive winds would seem to offer the most effective means of control. Vegetative covers are also a very effective means of controlling water erosion. Cropping systems, tillage practices, and moisture conservation measures which encourage vegetative growth therefore contribute to control of both wind and water erosion.

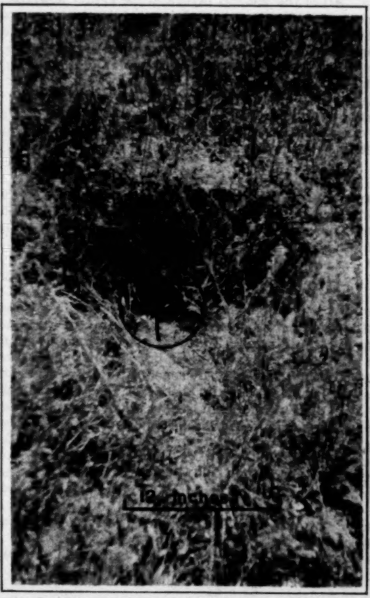
It is perhaps significant to note, however, that periods of protracted drought and high temperatures which limit vegetative growth in the Plains states tend to be periods of intense and frequent winds. In general, therefore, it seems that vegetative measures are less effective in control of wind erosion than in control of water erosion, under extreme conditions. The response of vegetation to greater amounts of precipitation increase its effectiveness as a means for control of erosion by water. But with erosion by wind the opposite is true because of the tendency for winds to occur in the Plains states during precipitation periods unfavorable for the growth of vegetation.

PIPING

Joel E. Fletcher, Karl Harris, H. B. Peterson, and V. N. Chandler

Abstract--Five conditions that must all be present for that type of erosion known as piping where the subsoil erodes out from under the surface to occur are as follows: (1) there must be a source of water, (2) surface infiltration rate must exceed permeability rate of some subsoil layer, (3) there must be an erodible layer just above the retarding layer, (4) water above the retarding layer must have a hydraulic gradient to make it flow, and (5) there must be an outlet for the lateral flow.

The insidious type of erosion known as "piping" [CARROLL, 1949; FLETCHER and CARROLL, 1948; FLETCHER and HARRIS, 1952], "tunnelling" [DOWNES, 1949], or "rodentless rodent erosion" [BOND, 1941], wherein the subsoil erodes from under the surface leaving tunnels, has been recognized by agricultural workers for a little over eleven years. The great majority of reports have approached the problem as though this phenomenon were a curiosity or an unusual occurrence. The investigations of the authors over the past six years have indicated that piping is widespread in western United States and occurs in at least the following countries: New Zealand, Australia, China, South Africa, and Turkey. While this type of erosion has been observed in upland areas of the United States similar to those studied by DOWNES [1949], the great concentrations are in alluvial bottom lands. Figures 6 and 7 show respectively a typical pipe inlet and outlet from a bottom land area.



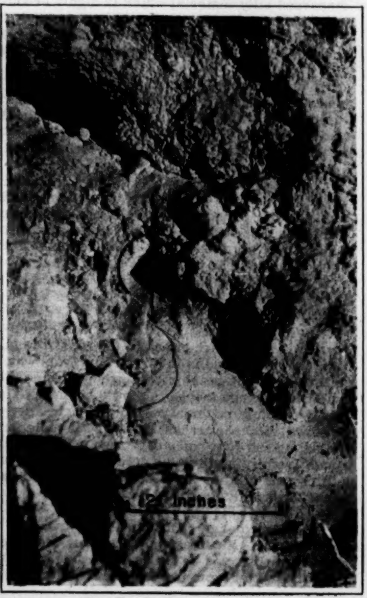


Fig. 6--Common type of pipe inlet in an alfalfa field

Fig. 7--Outlet to pipe in A

The authors have postulated that the five following conditions must be present before piping can take place: (1) There must be a source of water. (2) The surface infiltration rate must exceed the permeability rate of some subsurface layer. (3) There must be an erodible layer immediately above the retarding layer. (4) The water above the retarding layer must be under a hydraulic gradient. (5) There must be an outlet for the lateral flow.

These postulates were tested by detailed studies on five of the principal piping areas of Arizona. It was found that all were present on each area.

Picacho area--The Picacho area is located just east of Picacho, Arizona, at the foot of the Picacho Mountains. The pipes (pipe-like channels) extend from several playa-like areas toward a shallow entrenched drainage way. At points where these intersect the highway and railroad they appear to be large cracks in the soil surface.

LEONARD [1929] reported the first "crack" was noted September 12, 1927, following "a severe rain and wind storm of the afternoon and night before." He concluded that this crack was of seismic origin since a seismic shock was recorded for that time. Additional cracks appeared in 1949, 1951, and 1952. Violent rain and wind immediately preceded each appearance, but as personally reported by Eldred Wilson to the authors in 1952, seismic shocks were absent.

The present investigation of the area disclosed that the so-called cracks all extended from one or more of the playa-like areas to the entrenched drainage way near the center of the piping area. During intense rains large volumes of water drain from the playa-like collection areas through the underground channels into the central drainage way. Slowly permeable layers were found in the soil at depths of 12, 54, and 185 inches. Overlying each of these layers is a highly dispersed silty material which is highly erodible. All of the subsoil layers slope gently down toward the center of the piping area where they are incised by the entrenchment of the drainage way. Thus it can be seen that these cracks are indeed pipes. The path of the pipes may be traced by the succulence and size of the desert vegetation which has its roots in the moisture in the pipes.

Dateland area--This area lies adjacent to the Gila River on the old flood plain west of Dateland. In contrast to the Picacho area, this one is under irrigation. The pipes originate in cultivated fields and all extend in a southeasterly direction to approach the river bed at a horizontal angle of about 45°. The last 1000 yards of their length is through the nonirrigated area, where their path may be traced by the succulence and size of the vegetation.

The source of the water is from irrigation. The pipe inlets are in the irrigation borders. These pipes are from one to 2.5 feet deep and large enough to drain all of the water from a border, necessitating construction of a dike around each hole before irrigation can be continued. Outlets are in the Gila river bed about a mile southeast of the inlets. The hydraulic gradients result from the fact that the subsoil slopes in a southeasterly direction at a rate of about two feet per 1000. The surface soil in contrast slopes east at about 2.5 feet per 1000. The less permeable layer is at a depth of about three feet below the soil surface. Immediately above this retarding layer is a highly dispersed silty material which is very erodible.

Roll area--This area lies just east of the Gila River in the so-called Roll-Welton Irrigation Project. The severe piping in the Roll area falls into two groups. The first is in abandoned farmland and the second is in virgin land from which mesquite stumps had been burned out preparatory to leveling. The soils in both groups are composed of highly stratified, recent alluvium. The surface two or three inches is slowly permeable but underlaid by about 24 inches of readily permeable, highly erodible material on top of a tight silty clay. In the first group, piping takes place in rodent burrows, ditches, cracks, or any other hole through the surface. In the second group, pipes follow the stump and root holes of burned out mesquite. The source of water for both groups is from the runoff from rainfall on the surrounding tight surface soil. The outlets are in ditches, small incised gullies, and rills or any other cuts deeper than two feet. The slope of the subsoil furnishes the necessary hydraulic gradient.

San Pedro area--The San Pedro area lies adjacent to the San Pedro River up and down stream from Benson. Pipes extend back from the deeply entrenched river channel on both sides. Some have been observed as far as 1.5 miles from the channel. They occur in at least three depths ranging at the outlet from two to 20 feet below the soil surface.

Infiltration capacity of the surface soil is in excess of two inches per hour. By contrast, the various tight layers only percolate water at the rate of 0.03 to 0.04 inch per hour. Although the whole soil mass is erodible, the fine sandy and silty loams that overlie the tight subsoil layers are excessively so.

The water originates from the many irrigated fields along the valley, and from natural waterways crossing the area. Rodent activity over a considerable portion of the area tends to increase the concentration of water, thus aggravating the piping.

The hydraulic gradient results from the slope of the various tight subsoil layers. The layers slope down from the valley sides more or less normal to the valley trough. At points where the river channel cuts either up or down these slopes, the pipes disappear or enter the channel at small angles.

The outlets to the pipes are in the San Pedro River channel and in its incised tributaries. In the more severely piped areas, one pipe may spill into the one next below; this in turn spills into a still deeper one. This procedure may be repeated several times before the last one empties into the river channel.

Whitewater Draw area--This area lies along both sides of the Whitewater Draw north and west of Douglas. The pipes extend only short distances from the incised stream channel, seldom exceeding 1/4 mile in length.

The soil in this area is very fine-textured and has a coarse buckshot structure. The small clods are sufficiently hydrophobic to act as though the soil were composed of poorly graded gravel. Under prolonged wetting, the clods gradually swell and congeal into a uniform mass, thus becoming impermeable to water from a practical standpoint. As the soil dries, the cloddy structure reappears.

In the virgin state, the vegetation was largely tobosa and sacaton grass subject to periodic inundation. Under this condition no pipes were present. When Whitewater Draw was incised, pipes began to extend throughout the area.

Piping in the Whitewater Draw area takes place as the soil surface dries and while the subsoil is still wet and swollen. Water infiltrates into the cloddy surface soil extremely rapidly. The rate may even exceed 20 inches per hour. In the wet swollen state, the subsoil has a premeability of less than one inch per hour. The highly erodible cloddy surface soil is washed out by the lateral flow toward the Draw.

The water source here is from the natural overland flow down the swale areas and from irrigation. Outlets are in Whitewater Draw and its feeder tributaries. The hydraulic gradient is caused by the natural slope of the land toward the stream channel. This gradient is increased by some piling up of water due to the excessive intake rate of the cloddy surface soil.

Soil properties--FLETCHER and CARROLL [1948] in their study of piping gave some analyses of three soils from the San Pedro area. They concluded that on these soils only those soil properties associated with exchangeable sodium correlated with permeability. Exchangeable sodium analyses for soils from the five sites studied are given in Table 4. These values for sodium in the

Table 4--Soil analyses from the piping areas

Sampling area	Depth	Base exchange capacity	Exchangeable sodium	Sodium in the exchange complex
	inch	Me/100 gm	Me/100 gm	pct
Picacho	1 - 4	9.00	0.31	3.4
	12 - 15	9.40	0.56	5.9
	54 - 57	13.30	0.40	3.0
	106 - 110	13.31	3.22	24.2
Dateland	0 - 3	15.22	6.91	45.4
	30 - 33	15.49	7.09	45.8
	42 - 45	16.10	7.20	44.7
Roll	15 - 18	12.20	6.32	51.8
	24 - 27	6.80	3.34	49.2
San Pedro	8 - 12	14.30	7.60	53.1
	34 - 38	24.00	17.50	73.0
	58 - 62	9.60	8.70	90.6
	8 - 12	13.20	3.20	24.2
	34 - 38	17.60	4.30	24.4
	58 - 62	12.90	0.90	7.0
	8 - 12	11.21	0.00	0.0
	22 - 26	15.69	1.10	7.0
	34 - 38	17.62	1.71	9.7
	58 - 62	16.30	0.59	3.6
Whitewater Draw	0 - 6	12.45	4.22	33.9
	6 - 10	15.75	0.97	6.1
	48 - 53	25.30	9.71	38.3
	56 - 59	24.65	10.66	43.3

complex range from zero to greater than 90 pct. In spite of this wide range, all of the soils are subject to piping. It appears, therefore, that while sodium may contribute to the severity of a piping condition, sodium is by no means necessary to the occurrence of piping.

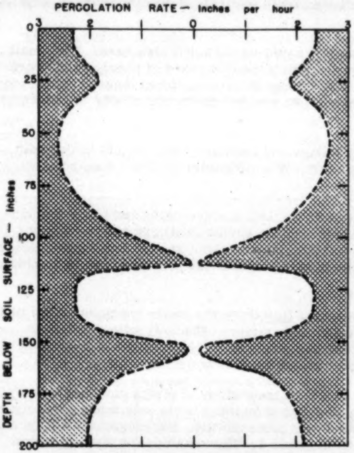


Fig. 8--Relationship of percolation rate to depth below the soil surface for soils similar to the San Pedro area

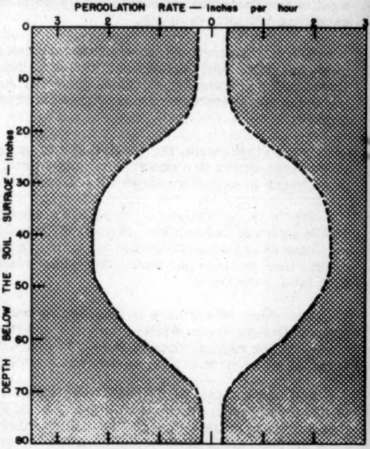


Fig. 9--Relationship of percolation rate to depth in the soil profile for soils similar to those from the Picacho

Figures 8 and 9 show typical curves for percolation rates at various depths in the soil profile. Figure 8 illustrates typical conditions in the San Pedro area and at similar sites. In areas with this type of permeability pattern, and when all of the other conditions necessary for piping are present, pipes may occur at several depths regardless of rodent activity or type of culture. Figure 9 illustrates permeability conditions of the Roll area and similar sites. In areas with this type permeability pattern and when all of the other conditions necessary for piping are present, pipes only occur when rodents or other activities allow the water to enter the soil surface at an accelerated rate.

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DISCUSSION

H. V. Peterson (U. S. Geological Survey, 503 Federal Bldg., Salt Lake City, Utah)--As my observation of piping and its effect has been limited to arid areas, this discussion will be confined to the phenomenon as it appears along ephemeral stream channels in some of the western arid valleys. The prevalence of piping along the banks of most western gully channels is such that anyone with any knowledge of the area could not have failed to observe it. From its distribution we may conclude that climate has little or no influence on piping since it is as likely to be found in Montana as in Arizona. Doubtless certain soil characteristics are favorable to formation of the underground pipes but such characteristics must have a wide span because the features will develop in soils derived predominantly from continental sandstone where the salt content would likely to be low, almost as readily as they will in soils derived from marine shales where the salt content is obviously high. Thus neither climate nor soil characteristics appear to be limiting factors in the formation of pipes.

Although our office of the U. S. Geological Survey has recognized piping as a part of the erosion menace for a long time, we have never attempted to set up the five conditions postulated by the authors as essential to their formation. The conditions do, however, appear to be entirely logical. We recognized that at least two essential conditions had to be present: (1) variation in the permeability of the soil layers, and (2) some means for introducing the water into the ground at a particular point in order to initiate the pipe. Since the piping usually occurs in transported alluvial soils, the thought has occurred to me that in forming underground the pipes may follow some minor feature of an earlier drainage pattern developed when the land surface was at the particular level of the pipe, perhaps a minor channel of some kind containing a slightly different type of fill or even an assortment of trash of some kind that when decomposed might add slightly to the permability of a particular part of a layer. I have observed no evidence supporting this idea, but it appears there might be some remote relationship to conditions existing during a former period of the valley floor formation.

An explanation of how the water gets into the ground and why a particular locality forms the focal point for development of the pipe presents an even more puzzling aspect. The presence of rodent holes, decayed root channels or other similar avenues for water percolation offers an obvious explanation and doubtless many of the pipes originated from features of this type. However, the evidence is conclusive that not all pipes have their source in rodent holes or root channels. In the San Simon Valley I have observed groups of pipe openings whose locations had the form of a large, crudely-shaped hexagonal, suggestive of sun-cracking. There seems little doubt that sun cracks, which sometimes attain a width of an inch or more when thoroughly dry, could act as a channel to convey water downward particularly when they were filled rapidly, but it is difficult to understand how sufficient water could be introduced in this manner to saturate a column of soil to the degree that it would loose stability and thus be subject to hydrostatic action and be capable of movement along a hydraulic gradient. It is my belief that considerable study is still needed before the mechanics of the piping action can be completely explained.

As an element in the erosion problem, piping has particular significance. The material excavated from the piping openings constitutes a substantial contribution of sediment to the channel. This can easily be observed in places where small fans are left at the mouths of the pipes when there has been insufficient flow in the parent channel to remove the waste. The piping also leaves the walls of gullies more vulnerable to erosion, since the walls in place of being relatively smooth, are left uneven and ragged by these openings, thus affording the flow a better opportunity to attack. Moreover, because the stability of these soils is materially reduced with wetting, the pipes aid erosion by providing additional avenues for wetting. It is not uncommon in the West to find areas containing several hundred square feet in which the subsoil has been completely removed or its stability has been so impaired that there has been subsidence of the surface amounting to two or three feet, usually leaving a jumbled mass of soil blocks on which the grass turf and shrubs are still likely to be in place.

Still another factor is the drainage effect of the piping. A network of the pipes is sufficient to drain subsurface moisture and one of the common sites along the banks of gullies, particularly in the Southwest, is a belt varying in width from a few feet to several hundred feet, completely barren of vegetation and thus subject to surface erosion. Examination will show that generally these belts are riddled with pipes that drain the soil to the point where plants can no longer survive. Eventually these belts deteriorate into the most destructive phases of erosion badlands.

There appears to be little that can be done to stop piping as such. Because it is associated with gullies or other types of deep channels, the only feasible treatment would appear to be to cure the gully. Once the deep channel into which the pipes discharge have been filled, thus cutting off flow, the pipes should in time fill of their own accord.

EROSION IN THE SAN GABRIEL MOUNTAINS OF CALIFORNIA

J. D. Sinclair

Abstract--Natural features of topography, geology, soil, and climate in the San Gabriel Mountains are all conducive to high rates of erosion. When the vegetation on steep slopes is removed as by fire, or the land surface is disturbed, erosion may be greatly accelerated through increased surface runoff. Flood flows bulked with debris have caused loss of life, sedimentation of reservoirs, and extensive property damage downstream. Removal of soil by erosion also adversely affects conditions on the mountain watersheds. Eroded material carried by flood runoff from the mountains greatly complicates problems of flood regulation and water conservation on valley lands below. Solution of these problems has been sought mainly through protection of the vegetation on the mountains from fire and by construction of extensive engineering works, the latter mostly downstream. Studies are being made by the U. S. Forest Service concerning sources, processes and rates of erosion on the mountain slopes, and of means to increase the stability of soils by improving the vegetation on areas where erosion is most severe.

Features of the area--The San Gabriel Mountains, one of the principal ranges in Southern California, extend about 80 mi east and west between the Mojave Desert on the north and the densely populated San Fernando, San Gabriel, and Santa Ana Valleys on the south (see Fig. 10). The mountains rise abruptly above the desert and valley lands less than 1000 feet in elevation to summits varying from 5000 to 10,000 feet high. They form an area of rugged relief marked by deep, V-shaped canyons and sharp ridges. The valleys south of the range have been filled in geologic time with material eroded from the mountains, and large alluvial fans extend out into these valleys.

Crystalline metamorphic rocks, mostly banded gneisses and schists, and igneous rocks consisting of quartz diorite, granodiorite, and anorthosite make up the principal mountain mass [STOREY, 1948]. The range has been very intensively faulted and fractured. As a result, some of the largest bodies of rock are very unstable and subject to rapid weathering. Uplifting of the mountains in geologic time rejuvenated the streams. Rapid down-cutting of stream channels and under-cutting of slopes have continued since this rejuvenation and contribute greatly to the instability of these mountains.

Mountain soils are nearly all residual and youthful, and are therefore closely related to the underlying parent rocks [COLMAN, 1948]. Most of the soils are shallow, and rock outcrops are abundant. Moderate- to coarse-textured soils predominate although some contain considerable clay. In general, the soils on steep slopes are subject to pronounced movement by gravity and are very erodible when exposed bare to rain and wind.

The Mediterranean climate of the area is characterized by long, warm and dry summers and wet winters with frequent below-freezing temperatures at higher elevations. Annual precipitation varies from about 20 inches on the lower slopes of the mountains to 40 inches or more on the summits. About three-fourths of the precipitation occurs during the four months December to March. During this winter period intense rainstorms are quite frequent and appreciable snow falls above 4000 feet. Very high rain intensities have been recorded in these mountains. In 1926, 0.65 inch of rain fell in one minute at Opid's Camp, a world record. On January 22, 1943, 26.13 inches of rain fell in a 24-hour period at Camp LeRoy, establishing a new record for the United States.

Brush, which is also known locally as chaparral, is the dominant vegetation on the San Gabriel Mountains and forms a characteristic feature of the landscape below elevations of about 5000 feet. This cover is composed of many different shrubs. The species and density of the vegetation vary in relation to age of the cover as well as to the amount of rainfall, depth of soil, and other site conditions. Open forests of several coniferous species form the principal cover above 5000 feet. These shrubs and trees are able to survive during the long, dry summer season. During this season, however, the vegetation, especially the chaparral, becomes very inflammable and the hazards of fire are exceedingly high. Records show that within the last 60 years most of the chaparral cover on the San Gabriel Mountains has been burned-over at least once, and in some places as many as three times. Chaparral has the ability to regrow naturally after a fire. Some of the shrubs sprout from the burned stumps. Other species are killed by fire but the heat stimulates germination of their seeds and new plants grow to replace those that were destroyed. Annual and short-lived perennial plants usually form the dominant though temporary cover for a few years after a fire. These plants later give way to the returning shrubs.

Topography, soil, and climate are all conducive to rapid land erosion. Opposing these are the stabilizing effects of the vegetation growing on the mountains. This vegetation with its accumulated

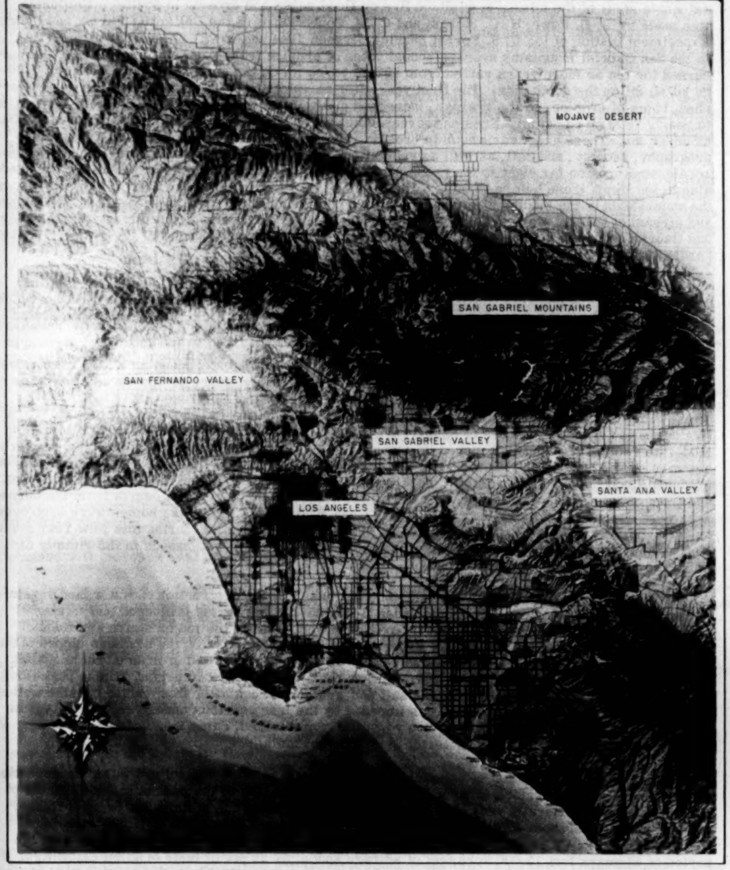
MOJAVE DESERT
SAN GABRIEL MOUNTAINS
SAN FERNANDO VALLEY
SAN GABRIEL VALLEY
SANTA ANA VALLEY
LOS ANGELES

Fig. 10--The San Gabriel Mountains of California form an area of rugged relief between the Mojave Desert on the north and densely populated valley lands on the south

litter of leaves, stems, and branches on the ground protects the soil from the beating of rain, and retards surface soil creep. Roots of the plants also aid in anchoring the soil and weathered rock. In addition, the vegetation retards erosion by reducing surface runoff. Nevertheless, erosion rates of 1000 to 3000 cu yd/sq mi annually are common from areas covered with vegetation.

Accelerated erosion--Land erosion in the San Gabriel Mountains can be greatly accelerated when the vegetation is destroyed by fire. This has been observed and recorded in a number of instances over many years, when even moderate rainfall occurred on recently burned slopes. An

extensive study of the effects of wildland fire on flood peaks and erosion in Southern California was made by P. B. Rowe, H. C. Storey, and C. M. Countryman, of the California Forest and Range Experiment Station of the U. S. Forest Service between 1944 and 1947. The results showed that in the San Gabriel Mountains average annual rates of erosion from watersheds with vegetation unburned for ten or more years varied from 450 cu yd/sq mi on the north side of the range to 6000 cu yd/sq mi on the south side. The first year after complete burning of the vegetation on a watershed, rates of erosion, on the average, increased about 15 times on the north side of the mountains, to nearly 7300 cu yd/sq mi. Erosion increased nearly 30 times on the south side, to about 78,000 cu yd/sq mi. These great variations in erosion rates were related to differences in rainfall, topography, geology, and soil, as well as vegetation. It was shown also that burning the vegetation accelerated erosion for eight to ten years subsequently, and during this period the rates averaged nine to ten times those before burning. These rates of erosion represent material delivered from the watersheds to the mouths of mountain canyons, and therefore include the erosion of both slopes and stream channels. Comparable effects of wildland fires on accelerated sedimentation in several San Gabriel Mountain watersheds were obtained in a subsequent study made by the Forest Service [ANDERSON, 1949].

Road construction is another serious type of disturbance of the vegetation and soil that may adversely affect the unstable conditions of nature in these mountains. Highway construction, which requires the loosening and exposure of large quantities of soil and rock, has greatly accelerated erosion in some watersheds.

Damages from erosion--Debris-laden floods from the San Gabriel Mountains have caused loss of life and extensive property damage downstream. A historic instance of this devastation occurred early on New Year's Day, 1934, in the cities of La Crescenta and Montrose [KRAEBEL, 1934]. These cities are built on alluvial fans in the valley south of Mount Lukens. In November, 1933, a fire destroyed some 5000 acres of chaparral cover on the steep southern slopes of this mountain. Moderate rainfall of about five inches occurred in mid-December. This was followed by a severe storm of over 12 inches during the period December 30 to January 1 inclusive. The second storm produced flood flows bulked with soil, rock fragments, and boulders from the fire-denuded slopes and from channels that were scoured by the flows. Nearly 600,000 cu yd of debris from the burned area were deposited in the valley. During this flood 30 lives were lost, 483 homes were destroyed or damaged, and property losses amounted to $5,000,000. In contrast, during this New Year storm no floods, but only moderate runoff and erosion, occurred in other watersheds in the vicinity on which the vegetation was long unburned.

Although the opportunities for disaster are increased by the destruction of watershed vegetation, it should be pointed out that debris-laden floods have come during prolonged and intense storms, from watersheds with good cover, long unburned. During the major storm and flood of March, 1938, studies on the San Dimas Experimental Forest (situated on the southern slopes of the San Gabriel Range) showed that there was very little surface runoff and erosion on the mountain slopes covered with vegetation, though streamflow peaks were of record height. These peak flows were produced by rapid seepage from the soil and weathered rock after this mantle became wetted and the downward movement of water was impeded by the less pervious underlying rock. Debris carried by the flood flows, up to 20,000 cu yd/sq mi of watershed, came mostly from the cutting of stream banks and the removal of material in stream channels.

The loss by sedimentation of valuable storage capacity in flood control and water conservation reservoirs is another serious form of damage caused by erosion in the mountain lands. Rates of sedimentation are generally very high. For example, nine reservoirs in the San Gabriel Range, with tributary watersheds totaling 380 sq mi, had original capacities totaling 87,000 acre feet [LOS ANGELES COUNTY FLOOD CONTROL DISTRICT, 1952]. These reservoirs in an average period of 17 years lost 18,000 acre feet of storage space, or 21 pct of their original capacities. If this rate of deposition continued, the average reservoir would be filled in 85 years. Sedimentation for the average period of 17 years totaled 76,000 cu yd/sq mi of tributary watershed, or nearly 4500 cu yd/sq mi annually. This rate of sedimentation was influenced by the accelerating effects of fires and road construction in some of the watersheds as well as the effects of the major flood in 1938. Therefore sedimentation may have been greater than the average would be for a longer period with fewer disturbances.

Erosion in the mountain lands has other consequences. The water in debris-laden stormflows often cannot be caught for use; much of it may therefore be wasted to the ocean. Such flows cannot be diverted to underground storage because the fine material carried by the water seals the surface of spreading grounds which are used to place water in underground storage in valley basins. Neither can flows be diverted and used for domestic and other purposes requiring clear water.

Erosion also adversely affects conditions on the mountain watersheds. Loss of soil, which may mean complete removal of a thin mantle, reduces the opportunity for water storage in the soil, and in other ways limits the development of the vegetation that protects the mountain lands. These conditions alter the hydrologic characteristics of watersheds by tending to increase flood runoff and reduce sustained water yield.

Prevention and correction--Solution of the flood regulation and water conservation problems that are so closely related to erosion in the San Gabriel Mountains has been sought mainly through protection of the mountain vegetation from fire and by the construction of extensive engineering works, the latter mostly downstream.

In the mountains prevention and control of wildland fires have been major activities for many years. From a very meager start more than 50 years ago, fire protection expenditures by Federal, State, and County governments now amount to several hundred thousand dollars annually. Millions of dollars have been invested also in improvements, equipment, and research to make fire-protection efforts as effective as possible.

Other measures have been taken in recent years to reduce excessive erosion in these mountains. Burned-over watersheds are seeded to mustard [GLEASON, 1948] and other plants to aid nature in developing a cover quickly on the denuded soils. The overcast and fill slopes of newly constructed roads are treated to stabilize the loosened material, making use of various techniques to provide protection and support for the soil by mechanical means combined with the use of vegetation [KRAEBEL, 1936; HORTON, 1949; BOWERS, 1950].

The first upstream flood control program of the U. S. Department of Agriculture to be approved under the Flood Control Act of 1936 was in Los Angeles River watershed [U. S. DEPARTMENT OF AGRICULTURE, 1941]. This program to retard flood runoff and erosion provides, on wild lands, for more intensive fire protection, engineering structures, road slope stabilization, and improvement of watershed vegetation on critical areas.

Downstream in the canyons and the valleys, major engineering works have been built for flood and debris control. These structures include debris basins, reservoirs, large retarding basins, and lined channels. About $200,000,000 have been spent, principally by the Federal Government and Los Angeles County, for these flood control works. The construction of similar works now planned will increase total expenditures to more than $500,000,000.

Debris carried by flood flows adds greatly to the problems and costs of downstream flood control. Structures must be built to cope with both debris and water, and the debris in some flows may amount to half or more of the total volume. Further, debris deposits impair or destroy the effectiveness of these structures. It is feasible, though costly, to excavate material caught in debris basins that are accessible at the mouths of watersheds, but it is impracticable to remove debris from reservoirs in the mountains by this method. As a partial solution to this latter problem, Los Angeles County Flood Control District is sluicing finer sediments from several of its reservoirs in the San Gabriel Mountains.

Current research--Erosion on mountain slopes is being investigated by the Forest Service in connection with the upstream flood-control program in Los Angeles River watershed. An initial study of the sources and processes of erosion was made in 1951 in 46 watersheds within this area, ranging in size from 20 to 234 acres, by John L. Retzer, of the Rocky Mountain Forest and Range Experiment Station, and reported in a manuscript entitled The Origin and Movement of Sediments in the Los Angeles River Watershed, California.

The inventory of physical conditions in the sample areas revealed that: (1) the surface area is 20 pct greater than the map area; (2) average slope of the land is 68 pct; (3) the angle of repose is approximately 70 pct; (4) 59 pct of the land is steeper than the angle of repose; (5) the areas contain 180 miles of drainageways; and (6) channel gradients average 44 pct, or 2300 ft/mi.

The sources of eroded sediments, in their approximate order of importance, were found to be: (1) stream banks and slopes rejuvenated by undercutting; (2) slopes with south exposures; (3) very steep upland slopes; (4) fault zones and steep fault faces; and (5) deep colluvial-alluvial deposits on upland slopes when undercut by roads or streams.

The active agents of erosion were observed to be gravity, water, wind, and the daily freeze-thaw cycle, the latter mainly at high elevations.

Sediment was found to move from the land mainly in two ways; as granular movements on the soil surface, and as deep-seated movements of soil masses. Granular sediments moved as dry creep and as slope wash. Both creep and wash were found active over all the area, but were especially active on south-facing slopes where the plant cover was sparse. Slides constituted the most common form of mass land movement, and undercutting was the most important disturbance causing slides.

A second study of erosion on slopes was started in 1952 to determine the amounts and rates at which soil materials move under long-unburned native vegetation, as influenced by topography, geology, soil, and aspect. The results are also expected to show soil movement variations by cause (gravity or water) and by seasons, as well as the kinds of material moved.

Increasing the stability of soils by improving the watershed vegetation is the objective of other investigations being made in Los Angeles River watershed by the Forest Service in cooperation with the California Institute of Technology. Possible ways are being studied to improve the stabilizing influence of the watershed cover by increasing the density of the native vegetation and by replacing the native vegetation with plants from other localities.

The broad objectives of this current research are to learn more about the processes of erosion on mountain slopes where soil movement starts, and to find how to bring about increased soil stability on slopes by vegetative means. The findings will constitute basic steps toward solution of the far-reaching problems of erosion in the San Gabriel Mountains.

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SUSPENDED SEDIMENT DISCHARGE AS RELATED TO STREAMFLOW, TOPOGRAPHY, SOIL, AND LAND USE

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Abstract--The results of suspended-sediment sampling were used to obtain average annual suspended sediment discharge from 29 watersheds of western Oregon by relating sediment-sampling results to streamflow and by using streamflow frequencies. The values of average suspended sediment thus obtained were related by regression analysis to average watershed values of two streamflow variables, two topographic variables, two soil variables, and one channel bank variable. The soil variables were functions of particle size and aggregation determined by analyzing samples of the surface soil taken at standardized locations in the major geologic types. The other variables were functions of data published in maps and other secondary sources. The regression results were used (1) to construct a map of the sediment producing potential of lands in western Oregon under average land use conditions; (2) to estimate how the actual production of sediment would differ from the potential with deviation of land use from average; and (3) to distribute present sediment production to the three major source areas: forest land, agricultural land, and channel banks of the main river.

Introduction

The suspended-sediment load of many streams has been measured in recent years. Estimates of the sediment discharge of the watersheds can be made from these measurements. The rates of sediment discharge thus obtained represent an integrated average of the sediment discharge from all parts of the watershed. The rates from individual parts of the watershed remain unknown. Between watersheds the discharge of sediment varies in response to differences in streamflow, soil, topography, and land use. Within the parts of a single watershed similar responses may be presumed to occur. The purpose of this paper is to report a study of the responses of sediment discharge to the following watershed variables: streamflow, soil, topography, and land use. These responses were used to estimate the contribution to sediment discharge of the individual parts of watershed with different values of the variables.

The locale of the study was the mountain and valley watersheds of western Oregon, from the California border to the Columbia River. Here records of suspended-sediment load were available for 29 streams for a period of one to three years. Information on streamflow, geology, topography, vegetation, and land use has been published, and some additional information on soils was determined by laboratory analysis of soil samples from representative areas of the watersheds.

Specifically, this study included (1) calculation of average annual suspended discharge of 29 watersheds, (2) regression analyses relating sediment discharge to watershed characteristics, (3) estimation from these relationships of the "erosion potential" for lands of western Oregon (erosion potential is defined as the expected average annual suspended sediment production if all lands, both forest and agricultura, were in the same condition--the average 1950 condition for the whole of western Oregon), and (4) an estimation of how much the actual erosion would differ from the erosion potential with deviations of land use from average.

Table 5--Relative discharge frequency, suspended sediment sampling results, and average annual sediment concentration for selected watersheds of western Oregon

Relative discharge[a]				Suspended sediment sampling						Average suspended sediment
				No. of samples	Per cent of days with ppm of					
Class	Average	Frequency	Total		<12.5	12.5-27.5	27.5-72.5	72.5-142.5	>142	
1	2	3	4	5	6	7	8	9	10	11
		pct								ppm
Calapooya River at Albany										
0.01- 0.1	0.05	27.0	0.0135	14	13.50	13.50	....	...	...	13.5
0.1 - 1.0	0.42	45.0	0.1890	19	7.10	37.90	....	...	...	18.0
1.0 - 2.0	1.38	15.0	0.2070	9	....	1.70	13.30	...	...	46.5
2.0 - 4.0	2.62	8.5	0.2227	8	....	....	7.44	...	1.06	65.0
4.0 - 8.0	5.20	3.35	0.1742	6	....	....	1.68	1.67	...	79.0
8.0 -16.0	10.00	0.93	0.0930	1	....	....	0.93	...	...	95.0
>16.0	20.40	0.22	0.0449	0	....	....	....	...	0.22[b]	200.0[c]
Mean	....	....	.....	..	7	20	50	108	170	62.8
Total	....	100	0.9443	57	20.60	53.10	23.35	1.67	1.28	...
Rogue River at Shady Cove										
0.01- 0.1	....	0	.....	0	....	....	....	...	...	...
0.1 - 1.0	0.75	68.00	0.5114	2	68.00	....	....	...	...	5.5
1.0 - 2.0	1.28	26.20	0.3354	9	23.30	2.90	....	...	...	7.1
2.0 - 4.0	2.42	5.26	0.1273	2	....	2.63	2.63	...	...	35.0
4.0 - 8.0	4.80	0.51	0.0246	1	....	....	0.51	...	...	50.0
8.0 -16.0	9.00	0.03	0.0027	0	....	....	....	0.03[b]	...	133.0[c]
>16.0	18.00	0	0	0	....	....	....	...	...	...
Mean	....	....	.....	..	5.5	20	50	133	...	11.3
Total	....	100	1.0014	14	91.30	5.53	3.14	0.03	...	...

[a] Relative discharge is the daily discharge divided by the mean annual discharge.

[b] Value is from frequency of discharge column; location in sediment class was by reference to trend line relationship similar to Figure 11.

[c] Obtained from trend line of a relationship similar to Figure 11.

The results, including a map of erosion potential prepared for western Oregon, should provide a useful guide to land and water managers in this area. The methods have application to suspended sediment analysis and erosion and sedimentation studies in other places.

Studies and analysis

Obtaining sediment discharge from sediment load data--The data used in calculating average annual suspended sediment discharge included depth-integrated samples of the sediment concentration of the streams. These samples were taken between December, 1948, and March, 1952, by the Corps of Engineers, by the Forest Service, and by the Bureau of Reclamation. The other data were stream discharge quantities and frequencies. These data were summarized in the form of a frequency table for each watershed. The form of the frequency table (Table 5) is shown for Calapooya and Rogue watersheds. Similar frequency tables were prepared for all watersheds and are available upon request. For convenience, in the tables all discharges were expressed as "relatives" by dividing the actual daily discharge by the mean annual discharge.

The steps in calculating average annual suspended sediment discharge were: (1) calculating the average suspended-sediment concentration of a discharge class; (2) weighting the average by the volume of water occurring annually in that discharge class; and (3) multiplying this weighted average concentration by the mean annual runoff. In step (1), the means of each sediment-concentration class (usually the means were 7, 20, 50, 108, and 200 ppm) were weighted by the per cent of days in a given discharge class. This computation gave the average suspended-sediment concentration of a discharge class (Table 5, Col. 11). When no sediment sample had been taken in a discharge class, the average suspended sediment was read from the trend line of a relationship between suspended sediment and relative discharge established for that watershed (Fig. 11). In step (2), the average suspended-sediment concentration of each discharge class weighted by the average annual volume of a flow occurring at that discharge (Table 5, Col. 4) gave average suspended-sediment concentration of all water in ppm. In step (3), this weighted average concentration times the mean annual runoff (Table 6, Col. 2) converted to millions of tons, gave average annual suspended-sediment discharge of a watershed in tons (Table 6, Col. 16). This was used as the value of the dependent variable, suspended sediment, for that watershed in the subsequent regression analyses.

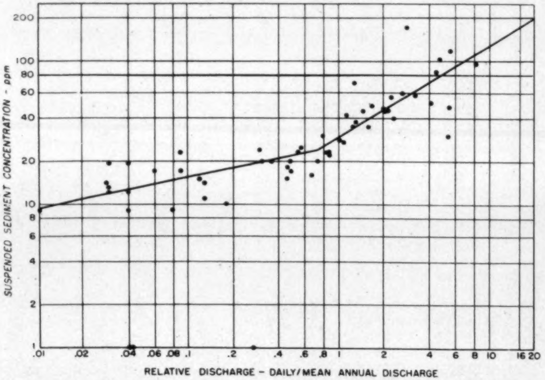

Fig. 11--Relation of suspended-sediment concentration to stream discharge, Calapooya River near Albany, Oregon, 1949 and 1950

This sediment-discharge-frequency method of obtaining total sediment from sampling results has three advantages over the sediment-hydrograph method described by the CORPS OF ENGINEERS [1948]: (1) Average annual sediment delivery is obtained directly, obviating the need to calculate sediment discharge for individual years; (2) not all the discharges during a year of sampling need be known, only the discharges at the time of sampling; and (3) the method is more rapid than the sediment-hydrograph method.

Table 6--Watershed characteristics and suspended sediment for selected watersheds of western Oregon

Watershed	Watershed characteristics[b]															Sediment discharge[b] SS 16
	A^a 1	MA_q 2	FQ_p 3	Se 4	SC 5	S/A 6	PF 7	RC 8	BC 9	OC 10	PC 11	R 12	S 13	EB 14	SSf 15	
	sq mi	$\frac{\text{cfs}}{\text{sq mi}}$		$\frac{\text{pct}}{100}$	pct	$\frac{\text{cm}}{\text{gm pct}}$	pct	pct	pct	pct	pct	pct	ft/mi	ft	M ton/yr	M ton/yr
Calapooya	362	2.29	3.28	3.1	20.9	0.52	7	5.6	10	27	17	0.60	630	1,600	16	51
Pudding	493	2.26	2.39	2.3	21.7	0.45	18	7.7	22	37	40	0.57	210	0	26	70
Mollala	323	3.21	3.90	3.6	20.4	0.56	24	15.8	4	12	28	0.22	1000	3,400	34	54
McKenzie	1310	3.80	3.27	9.6	19.9	1.04	20	7.1	2	5	22	0.10	1100	16,700	93	149
N. Santiam	665	4.76	3.55	8.6	20.1	0.96	9	5.6	0	4	9	0.12	1500	0	59	190[c]
Long Tom	100	2.52	3.81	3.9	24.2	0.61	36	21.1	3	16	39	0.30	660	0	12	8
Coyote	100	1.40	3.58	3.1	24.4	0.47	6	0	11	16	17	0.45	480	0	3	8
Willamette	991	2.64	2.44	15.4	19.8	1.46	4	1.9	0	1	4	0.11	960	6,800	53	53
Tualatin	568	2.12	3.03	1.7	29.2	0.29	13	2.4	19	48	32	...	.....	.....	..	53
Santiam	1790	4.10	3.62	5.6	20.3	0.72	10	6.3	3	11	13	0.23	1510	25,500	154	457
Coast Fork	69	2.77	4.23	3.9	20.2	0.59	22	17.1	1	1	23	0.12	480	0	5	5
Marys	155	2.84	3.58	3.7	24.1	0.59	20	1.4	4	26	24	0.38	830	0	12	19
Willamette	7280	3.05	3.24	6.2	21.1	0.76	12	4.3	6	19	18	0.43	1200	204,800	464	1955
Willamette	2030	2.50	3.64	7.3	20.2	0.84	4	1.9	2	6	6	0.17	1290	30,300	103	248
Row	211	2.63	4.27	4.0	20.1	0.59	5	0	1	1	6	0.21	1150	0	12	13
Luckiamute	236	3.74	3.61	3.7	24.1	0.59	8	0	6	44	14	0.40	710	0	14	27
S. Santiam	640	4.28	4.23	3.9	20.2	0.59	8	2.6	1	4	9	0.16	1290	0	60	88
S. Yamhill	502	3.19	3.18	1.8	29.7	0.28	12	5.0	18	32	30	0.53	490	0	42	82
Calapooya	(98)	2.30	3.96	4.2	24.9	0.90	20	5.6	0	4	20	...	...	....	..	23
Elk Creek	(85)	1.53	3.90	11.5	24.8	1.06	4	4.4	0	9	4	...	...	....	..	12
S. Umpqua	454	2.02	4.26	4.6	20.5	0.62	2	0	0	2	2	...	...	....	..	62
S. Umpqua	1640	1.51	4.06	6.8	25.6	0.71	9	1.1	0	4	9	...	...	....	..	182
S. Coquille	169	4.25	3.90	6.0	26.9	0.60	16	6.8	0	3	16	...	...	....	..	86
Illinois	367	2.92	3.90	8.2	28.8	0.68	10	4.9	1	6	11	...	...	....	..	85
Big Butte	(243)	1.04	1.98	17.6	19.1	1.78	12	0	0	5	12	...	...	....	..	3
Elk Creek	133	1.25	4.30	4.0	20.1	0.59	7	0	0	5	7	...	...	....	..	2
Rogue	(1190)	1.96	2.21	16.6	19.6	1.60	7	0	0	5	7	...	...	....	..	26
Wilson	(56)	5.89	3.90	2.0	32.0	0.26	80	30.4	0	0	80	...	...	....	..	21
Wilson	159	7.48	3.90	2.0	32.0	0.26	81	16.3	0	1	81	...	...	....	..	134
Mean	773	2.97	3.56	6.0	23.0	0.73	17	6.0	4	12	21	0.30	910	17,000	68	144

[a] Parentheses indicate area crudely estimated.

[b] Definitions of variables given in text, under the headings relating to variables.

[c] This value thought to be inordinately high due to stream disturbance during construction of Detroit Dam.

Relating sediment discharge to watershed characteristics--Sediment discharge varies with differences in watershed characteristics, which include streamflow, soil, topography, bank conditions, and land-use. Variations in these between watersheds permit evaluation of their individual effects on sediment discharge. The evaluation is possible by regression analysis which relates suspended sediment discharge from many watersheds to quantitative expressions of the characteristics of each watershed [GOTTSCHALK, 1947; ANDERSON, 1949, 1951; and GOTTSCHALK and BRUNE, 1950].

Specific variables were chosen to give quantitative expression to the watershed characteristics. Two requirements were made of a variable: (1) that it be expected to be related to sediment discharge, and (2) that it be expressible in terms applicable to individual land areas within watersheds. The second requirement was imposed because eventually the regression results were to be applied to calculate the contribution of individual land areas to sediment discharge.

The value of a variable for a watershed was obtained by averaging values of the variable as found in the individual land areas within the watershed. Peakedness of streamflow was averaged by weighting according to areal extent and a function of rain and snow-melt frequencies. All other variables were averaged by simply weighting by the areal extent.

The variables selected are listed below together with the methods used in obtaining the variable. In the section on results additional details are given on the methods used in obtaining the slope S and the soil variables SC and S/A. Quantitative values of each of the variables for each watershed are given in Table 6.

Dependent variables (suspended-sediment discharge)--The following were used:

SS	Suspended sediment; the average annual suspended sediment from a watershed under 1950 watershed condition (obtained from sediment sampling); unit, thousand of tons/yr; mean, 144; range, 2 - 1955.
ss	Same as SS except unit is tens of tons/sq mi yr; mean, 18; range, 1 - 84.

Independent streamflow variables--The following were used:

MAq	Mean annual runoff, obtained from U. S. Geological Survey Water Supply Papers; unit, cfs/sq mi; mean, 2.97; range, 1.04 - 7.48.
FQp	Discharge peakedness, based on a separate regression analysis which related peak discharges from watersheds to geologic rock types, to the area receiving rain during storms, and to the area in which snow was ripe during the storms (see Flood hydrology of forest watersheds, by Henry W. Anderson, California Forest and Range Experiment Station, 15 pp typewritten, Jan. 2, 1950); quantitative values of the relative peakedness variable may be obtained for western Oregon watersheds from a geologic map and Table 7; unitless; mean, 3.56; range, 1.98 - 4.30.

Table 7--Quantitative peakedness variable

Geologic type	Symbol[a]	Relative peakedness	Relative rain area frequency	Relative snow melt frequency	FQ_p[b]
Recent alluvium	Aa	1.0	0.97	1.00	1.0
Younger volcanic	Qv	2.0	0.20	0.30	0.6
Young volcanic	Qpv	2.0	0.53	0.66	1.2
Old volcanic	PMv	5.0	0.82	0.96	4.3
All other	c	4.0	0.96	0.99	3.9

[a] Geologic map of United States, U. S. Geological Survey, 1932.

[b] Relative peakedness times (1.2 relative rain area frequency plus 1.0 relative snow melt frequency) divided by 2.2 gives FQ_p.

[c] Mostly marine sediments, but some very old volcanics included.

Independent topographic variables--The following were used:

A	Area of watershed; unit, sq mi; mean, 773; range, 56 - 7280.
S	Slope of streams of one mile mesh length after method of HORTON [1945] (see derivation in section on results); unit, ft/mi; mean, 910; range, 210 - 1510.

Independent soil variables--The following were used:

Se	Soil erosibility; generalized variable of soil characteristics obtained from soil measurements developed by MIDDLETON [1930]; dispersion ratio times suspension times ultimate silt plus clay divided by 100 times the aggregated silt plus clay; unit, pct/100; mean, 6.0; range, 1.7 - 17.6.
SC	Silt and clay; fraction of top six inches of soil with particle sizes of less than 0.05 mm in diameter; unit, pct; mean, 23.0; range, 19.1 - 32.0.
S/A	Surface aggregation ratio; surface area on soil particles of sand and coarser size (>0.05 mm diameter) divided by the aggregated silt plus clay; surface area was obtained by considering the particles as spheres and assigning mean diameters of 7.5, 3.5, and 0.9 mm to the >5, 2 to 5, and 0.05 to 2.0 mm particle-size classes, respectively; aggregated silt plus clay was the ultimate silt plus clay, minus the suspension per cent; unit, cm^2/gm pct; mean, 0.73; range, 0.26 - 1.78.

Independent land-use and channel-bank variables--The following were used:

PC	Poor cover; portion of watershed with poorly stocked or non-stocked forest land or land in bare cultivation (data from same sources as RC and BC below); unit, pct; mean, 21; range, 2 - 81.
PF	Poorly stocked forest; portion of watershed in poorly stocked or non-stocked forest land (data from same source as RC below); unit, pct; mean, 17; range, 2 - 81.

R	Roads; portion of watershed area in roads; road lengths measured from National Forest maps of the Forest Service and Land and Water Inventory maps of the Soil Conservation Service; road widths taken as follows: primary state highways, 50 ft; secondary state highways, 40 ft; county roads, 32 ft; forest roads, 20 ft; and railroads, 15 ft; unit, pct; mean, 0.30, range, 0.05 - 0.60.
RC	Recent cut-over; portion of watershed area cutover in last ten years, read from Forest Service Forest Survey maps; unit, pct in 10-year period; mean, 6.0; range, 0 - 30.4.
BC	Bare cultivation; portion of watershed in row crops and small grain, from Soil Conservation Service Land and Water Inventory Maps; unit, pct; mean, 4; range, 0 - 22.
OC	Other cultivation; portion of watershed area in cultivation other than bare cultivation (source of data same as for BC, above); unit, pct; mean, 12; range, 0 - 48.
C	Cultivation; area of watershed in bare and other cultivation; (BC + OC) times A of Table 6; unit, sq mi; mean, 8; range, 0 - 67.
EB	Eroding banks; length of eroding main channel banks as given by the CORPS OF ENGINEERS [1950]; unit, ft; mean, 17,000; range, 0 - 204,800.

Calculated sediment discharge variables--The following were used:

ss3	Calculated sediment from streamflow and area variables, using Eq. (2); unit, tens of tons/sq mi yr; mean, 15; range, 2 - 43.
ss7	Calculated sediment from Eq. (3); unit, tens of tons/sq mi yr; mean 18; range, 4 - 102.
SSf	Sediment from forest lands of a watershed, read from the map (Fig. 12) and adjusted for deviation of recent cut-over, RC, from average; adjustment factor = antilog [0.0086 (RC-6.1)] from Eq. (5); unit, thousands of tons/yr; mean, 68; range, 3 - 464.

Regression analyses--The general method of analysis was multiple regression [SNEDECOR, 1946, p. 340]. However, because of the large number of variables which were expected to be important, the analysis was performed in five steps. The first step was to test the relation of sediment discharge SS to mean annual streamflow MAq, and peakedness of streamflow FQp, including in the analysis generalized expressions of other watershed variables. The generalized variable for topography was the area A; for soil, the soil erosibility Se; and for land use, the poor cover PC. Eq. (1) was the result.

The second step was the use of the partial effects of MAq, FQp, and A found in the first test, with the appropriate constant (2) to calculate sediment discharge ss3 for each watershed based on these variables alone.

The third step was to test the relation of actual sediment discharge ss, to this calculated sediment discharge ss3 and to some additional variables, soil silt plus clay SC, soil surface-aggregation ratio S/A, bare cultivation BC, other cultivation OC, and poorly stocked forest PF.

In the fourth step, similar to the second step above, the seven variables previously evaluated as the partial effects of ss3, SC, S/A, BC, and OC (3) were used to obtain another calculated value of sediment discharge from the watersheds, ss7.

The fifth step, similar to the third step, was to test the relation of actual sediment discharge ss to this calculated sediment discharge ss7 and to the final additional variables, road area R, recent cut-over area RC, and slope S. The result was (4), which when the specific variables are re-inserted for ss7, gave (5).

Eq. (6) was developed from analysis of 17 watersheds in the Willamette Basin for which the CORPS OF ENGINEERS [1947] had made estimates of the lengths of eroding banks. A test was made of the relation of the actual sediment discharge, SS, from the 17 watersheds to the length of eroding banks EB the calculated sediment discharge from forest lands SSf and the area of cultivated land C with (6) being the result.

Results of regression analyses--The regression equations follow, with logarithms being to the base 10:

$$\log SS = -2.717 + 1.163 \log MAq + 1.109 \log A + 1.566 \log FQp + 0.211 \log \log e^{PC} + 0.0295 \log Se \qquad (1)$$

$$\log ss3 = -0.516 + 1.163 \log MAq + 0.109 \log A + 1.566 \log FQp \qquad (2)$$

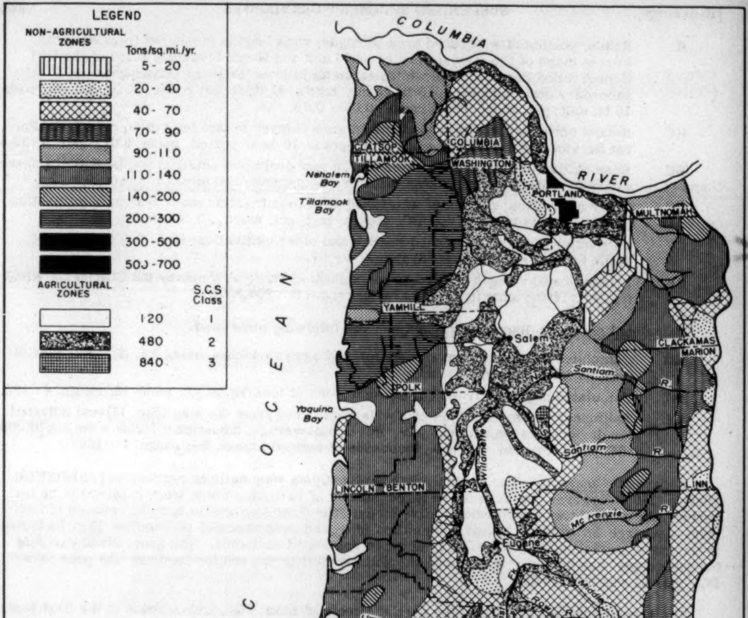
LEGEND
NON-AGRICULTURAL ZONES
Tons/sq.mi./yr.
5- 20
20- 40
40- 70
70- 90
90-110
110-140
140-200
200-300
300-500
500-700
AGRICULTURAL ZONES
S.C.S Class
120 1
480 2
840 3
COLUMBIA
RIVER
CLATSOP
TILLAMOOK
COLUMBIA
WASHINGTON
PORTLAND
MULTNOMAH
Nehalem Bay
Tillamook Bay
YAMHILL
Salem
CLACKAMAS
MARION
Santiam
POLK
Yaquina Bay
P A C I F I C   O C E A N
Willamette
LINCOLN
BENTON
LINN
Mc Kenzie
Eugene
Umpqua
COOS
Coos Bay
LANE
DOUGLAS
Roseburg
CURRY
N
JOSEPHINE
JACKSON
Rogue
Gold Beach
Grants Pass
0 10 20 30 40 50
Scale in Miles
O R E G O N
C A L I F O R N I A

Fig. 12--Erosion potential for land areas of western Oregon, defined as the expected average annual suspended-sediment production if all lands, both forest and agricultural, were in the same condition, the average 1950 condition in the whole of western Oregon

$$\log ss7 = -1.169 + 0.901 \log ss3 + 0.0410\ SC + 0.406\ S/A + 0.0236\ BC - 0.0030\ OC - 0.0003\ PF \qquad (3)$$

$$\log ss = -1.715 + 1.186 \log ss7 + 0.942\ R + 0.0085\ RC + 0.401 \log S \qquad (4)$$

$$\log ss = -3.721 + 0.116 \log A + 1.673 \log FQp + 1.244 \log MAq + 0.401 \log S + 0.0486\ SC + 0.482\ S/A + 0.0280\ BC - 0.0036\ OC + 0.942\ R + 0.0086\ RC \qquad (5)$$

$$SS\text{-}SSf = -1.639 + 0.240\ C + 0.00514\ EB \qquad (6)$$

An indication of the overall efficiency of the equations is given by comparing the observed sediment discharge with that computed by using the equations. Such a comparison for all 29 watersheds of the study, using (5) to obtain computed values, is shown in Figure 13. (Mean values of 0.30 and 9.1 were used for R and S in the equation when specific values were missing.) For those 17 watersheds of the Willamette Basin for which data on eroding banks were available, a comparison of the observed sediment discharge with that computed by (6) is shown in Figure 14. The comparisons indicate that a satisfactory separation of the high from the low sediment producing watersheds can be made by using the equations. Of equal importance, however, are the regression coefficients of the individual variables in the equations, for they are measures of the importance of various "causes" of sediment discharge from watersheds.

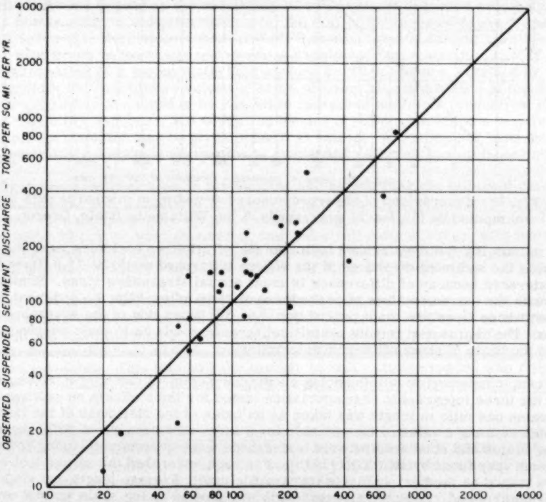

Fig. 13--Comparison of observed suspended-sediment discharge with that computed by (5), for 29 watersheds of western Oregon

Streamflow characteristics influencing suspended-sediment discharge--Two variables, the mean annual runoff and the peakedness of runoff, were used to characterize the streamflow in the watersheds. Both variables were highly significant in relation to sediment discharge.

The effects of mean annual streamflow and discharge peakedness on sediment discharge are given by the partial regression coefficients of 1.24 for MAq and 1.67 for FQp in (5). An index of the quantitative variation of sediment discharge which was associated with streamflow differences between watersheds may be obtained by substituting the extreme values of MAq and FQp from Table 6 in (5). For example, substituting for MAq the values 7.48 cfs/sq mi for Wilson watershed and

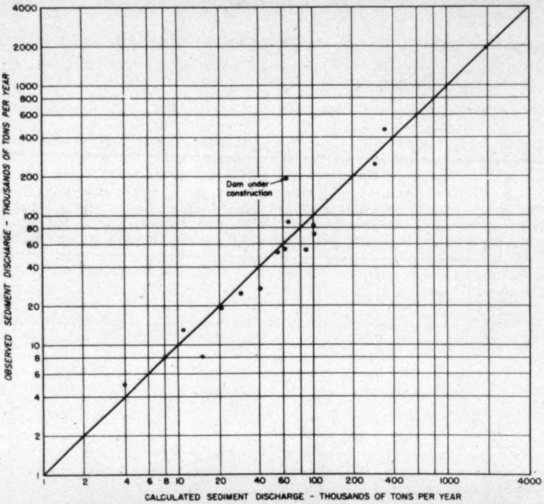

Fig. 14--Comparison of observed suspended-sediment discharge with that computed by (6), for 17 watersheds of the Willamette Basin, Oregon

1.04 cfs/sq mi for Big Butte watershed indicates that if all other variables were the same for the two watersheds the sediment discharge of the Wilson watershed would be 11.6 times that of the Big Butte watershed because of differences in mean annual streamflow alone. Similarly, between watersheds with the extreme values of peakedness of streamflow FQp, the sediment discharge of the watershed whose flows are most peaked would be 3.7 times that of the watershed with the least peaked flows. The regression results permit rating watersheds as to their suspended-sediment discharge on the basis of streamflow characteristics.

Topographic characteristics influencing suspended-sediment discharge--Slope, area, and elevation were the three topographic characteristics tested for their effects on sediment discharge. Slope of streams one mile in length was taken as an index of the steepness of the land areas. Difficulties in determining a value of the variable for a watershed because of differences in topographic mapping scales and standards between watersheds were overcome by using some relations of stream physiography found by HORTON [1945]. For each watershed the streams of each order number were traced on the best available topographic map. Average length and slope of each order number were determined. Average stream length was plotted on log scale against order number on arithmetic scale [see HORTON, 1945, Fig. 10], a trend drawn, and the order number of the streams of one-mile length read off to the nearest tenth of an order number. Then the average stream slope was plotted against order number [see HORTON, 1945, Fig. 6] and the slope corresponding to the order number of streams one mile long was read off. In the regression analysis this slope variable, the slope of the streams of one-mile length, was significant at about eight to one odds against a chance effect.

The effect of differences in slope on sediment discharge is given by the regression coefficient of 0.401 for S in (5). The magnitude of the effect may be indicated by substituting in the equation the greatest and least values of S for the watersheds given in Table 6. Such a substitution indicates that the watershed with the greatest slope would have sediment discharge 2.2 times that of the watershed with the least slope because of the slope difference alone. The regression results permit rating watersheds as to their suspended-sediment discharge based on a slope characteristic.

Sediment production per unit area varied very little with area of watershed when other variables of the watershed were taken into account. (The regression coefficient for the area variable A in (1) is nearly unity.) Elevation was not indexed separately but was a factor included in the rain and snow-melt frequencies in the streamflow peakedness variable FQp.

Soil characteristics influencing suspended-sediment discharge--The problem in evaluating soils was, how could the characteristics of the soils which influence sediment production be determined and used? Four steps were involved: sampling the soil, measuring the physical characteristics of the soil, relating the physical characteristics to measured sediment production, and applying the results in rating of soil as to erosibility.

Sampling the soils of a watershed--Determining the soil characteristics of a watershed by sampling was largely a problem of how to minimize the number of samples without undue loss of information. It was not feasible to sample all of the infinite variation in soils. Soil variations may be associated with every combination and level of each of the soil-forming factors: parent material, topography, climate, organisms, and time [JENNY, 1941, p. 15]. In soil sampling some sort of selection and averaging must obviously be resorted to. Therefore, some standard conditions of certain soil-forming factors were set up under which all soil samples were taken.

What variability in soil-forming factors should be sampled and which excluded by selection of the standard conditions depend on the variability of soils and the dominant erosion processes in the study area. In this study of sediment discharge, the soil of the forested areas of the watersheds was youthful and profile development was limited; therefore, it was thought possible to restrict soil sampling to differences in the single soil-forming factor--parent material. JENNY [1946] has called this a determination of a parent material sequence or lithosequence, obtained by arranging in order of magnitude the quantitative values of some physical characteristics of the soils. If these physical characteristics are found to be related to measured sediment production, the lithosequence becomes an erosibility sequence, and within the errors of determination, the relative erosibility of the types of parent material may be given numerical values. When this has been done an evaluation of the soil erosibility in terms of production of suspended sediment has been obtained.

A geologic map furnished a basis for locating and segregating the different parent materials in the 29 watersheds. Soil samples of the zero- to six-inch depth of soil were taken in each of the geologic types. The samples were all taken under a single set of conditions defined as standard: at slopes of about 30 pct, on west exposures, and under full natural cover, with the attempt being made to take samples at elevation of 2000 feet and where mean annual precipitation was about 60 inches. (The last two conditions could not be met for all geologic types.)

Differences in soils attributable to geology were measured from these soil samples, taken at the defined standard conditions in each geologic type. These soil differences may be evaluated for their effect on sediment discharge. The effects on sediment discharge of differences in soil in areas where runoff, topography, and land use were different from the standard condition were evaluated by the watershed variables. This was how the number of soil samples needed was reduced to feasible limits. In the forest-land areas, 42 soil samples were taken, three samples in each of the 14 major geologic types.

Measuring physical characteristics of the soils--The soil samples were analyzed in the laboratory. The analyses measured physical characteristics which MIDDLETON [1930] found to be qualitatively related to erosion and which had been found quantitatively related to sediment production in a recent study in Southern California [ANDERSON, 1951]. These characteristics are: particle size distribution from gravel through clay, and the suspension per cent. Sieving was used to determine soil fractions with diameters greater than two mm. Particle size distribution smaller than two mm was determined by the hydrometer method [BOUYOUCOS, 1936]. The dispersion procedure for the ultimate silt plus clay analysis was: two grams of sodium hexametaphosphate were added to about 35 grams of soil in 200 cc of water, and the mixture was stirred in a milk-shake machine for ten minutes. The hydrometer method was also used in analyzing particle size distribution in the undispersed soil in obtaining Middleton's suspension per cent.

Relating soil characteristics to measured suspended sediment--Once the laboratory measures were obtained, it was necessary to test which of these measured characteristics of soils were different for different soil types. It was reasoned that unless a soil characteristic was different between soil types, it could not possibly be diagnostic in explaining differences in sediment discharge. Therefore, an analysis of variance was used to test the significance of differences between soil types in some physical characteristics expected to be related to erosibility. The characteristics, in decreasing order of significance, were: surface area of particles coarser than 0.05 mm diameter, aggregated silt plus clay, Middleton's dispersion ratio, ultimate silt plus clay, Middleton's suspension per cent.

The next problem was to choose from among the soil characteristics, those which should be related to physical processes in suspended-sediment discharge. Two processes were considered: (1) the supply process, represented by the component of the soil which produces the fraction of erosion which is caught and measured as suspended sediment; ultimate silt plus clay was taken as an index of the supply factor; (2) the binding process, represented by the fraction of the soil which tends to bind the soil together versus the amount of soil surface in the non-binding fraction which requires binding. The surface area of particles coarser than 0.05 mm diameter divided by the aggregated silt plus clay was taken as an index of how effectively the soil was bound. It was called the surface-aggregation ratio.

The soil characteristics for the 14 major soil-geologic types of western Oregon are given in Table 8, Col. 3 - 10. Weighting each of these by the per cent of area of each type in a watershed gave average values of the soil variables for the watersheds, Table 6, Col. 4 - 6. Including the two soil variables in regression analyses (3) gave a measure of the significance of soil differences in affecting sediment discharge. The test of significance indicated 19 to one odds against a chance effect. The quantitative effects of soil variations were obtained by using the regression coefficients for the silt plus clay SC, and the surface-aggregation ratio S/A from (5) to calculate the relative erosibility of the soil developed on the various geologic types. The resulting relative soil erosibility for the 14 geologic types is given in Table 8, Col. 11. It may be seen that the most erosible soil, that developed on the Eocene volcanic, is 11 times as erosible as the soil developed on alluvium. The geologic map, together with these ratings of erosibility, locate and evaluate the differences in suspended-sediment discharge attributable to soil.

Table 8--Physical characteristics of surface soil and relative erosibility of major soil-geologic types of western Oregon

Geologic types	Geological symbol[a]	Particle size distribution diameters-mm				Suspension[b]	Aggregated si + cl[c]	S/A[d]	Se[d]	Relative erosibility[e]
		<0.05	0.05-2	2-5	>5					
		pct	pct	pct	pct	pct	pct	$\frac{cm^2}{gm\ pct}$	$\frac{pct}{100}$	
Alluvium	Qa	25.1	10.6	27.6	36.7	5.7	19.4	0.37	143	0.7
Recent volcanic	Qv	16.9	73.5	5.3	4.3	10.2	6.7	2.75	2450	7.7
Young volcanic	QPv	19.6	54.9	12.0	13.5	11.0	8.6	2.04	2290	4.7
Columbia basalt	PMv	20.1	20.2	26.2	33.5	6.8	13.3	0.59	420	1.0
Miocene marine	Mm	32.0	10.4	31.9	25.7	8.6	23.4	0.26	227	2.6
Oligocene marine	Øm	24.9	16.4	34.6	24.1	7.1	17.8	0.41	329	1.8
Eocene marine	Em	24.2	19.1	28.2	28.5	7.2	17.0	0.62	427	1.6
Eocene volcanic	Ev	40.5	12.6	26.8	20.1	10.0	30.5	0.17	182	6.2
Cretaceous marine	K	31.0	27.0	23.8	18.2	15.4	15.6	0.57	858	3.3
Jurassic Triassic	JTR	19.4	14.1	28.7	37.8	6.1	13.3	0.53	331	0.9
Old intrusive	Ji	20.2	50.6	22.8	6.4	10.8	9.4	1.64	1660	2.8
Carboniferous volcanic	Cv	30.9	34.9	20.9	13.3	13.6	17.3	0.68	891	3.7
Carboniferous	C	31.1	22.4	23.6	22.9	17.8	13.3	0.60	1070	1.8
Devonian	D	25.2	6.7	22.2	45.9	5.9	19.3	0.23	189	1.2
Agricultural[f]	. .	19.5	3.8	57.4	19.3	4.6	14.9	0.35	101	...

[a] Geologic Map of United States, U. S. Geological Survey, 1932.

[b] MIDDLETON [1930]; all percentages given are per cent of whole soil.

[c] Ultimate silt plus clay (particles < 0.05 mm in diameter) minus suspension.

[d] Defined in text.

[e] From (5) using particle size < 0.05 mm for SC and values of S/A from this table; relative values assigned by taking PMv geology as 1.0.

[f] Based on two samples.

Land-use characteristics influencing suspended-sediment discharge--Four land-use characteristics were analyzed for their effects on sediment discharge. These were (1) the recent cut-over area, measured from detailed county maps prepared by the Forest Survey of the Forest Service; (2) the cultivated area, measured from the Land and Water Inventory Maps of the Soil Conservation Service; (3) the length of eroding main channels, measured by the CORPS OF ENGINEERS [1950]; and (4) the area of roads, measured from maps used for first two characteristics.

Recent cut-over and roads together had a highly significant effect on sediment, as did eroding banks. Cultivation was significant at about ten to one odds. Thus, sediment discharge was found to increase as the area of recent cut-over, bare cultivation, and roads increased and with the increases in the length of eroding main channel banks. The regression coefficients of (5) and (6) permit estimation of the quantitative effects of land-use and eroding channel banks on sediment discharge.

If timber cutting were to increase from the present annual cut of 0.6 pct of the watersheds to 1.5 pct, which would result from full utilization of the forest on a 70-year rotation of cutting, then the regression results indicate that suspended sediment would increase by 18 pct due to the cutting alone. However, the associated probable increase in road development might have a much greater effect. If future roads, built to the same standards and hence having the same effects as present roads, were to occupy 0.55 pct of the forested watersheds instead of the present 0.1 pct, then, the regression results indicate that the suspended-sediment discharge would be 2.6 times as great. Together logging and road development in the future could increase sediment discharge by three times if no preventive measures are taken.

Control of erosion from cultivated lands and eroding main channel banks would markedly affect sediment discharge. The regression results indicate that conversion of bare cultivated land to other types of cultivation would nearly eliminate the converted land as a source of suspended sediment. Control of eroding banks of the main channels would reduce sediment discharge by five tons per year per running foot of eroding bank.

In all, the study indicates that a large part of the present or potential sediment discharge is attributable to land-use and channel bank condition. To some degree these are subject to control. Obviously a reduction in the area occupied by the several kinds of present land-use or in the length of eroding channel bank could reduce sediment discharge. But modification of present land-use methods might also lead to significant reductions in sediment discharge, even though the area subject to use were extended. Discussion of such modifications, and their effectiveness, is beyond the scope of this paper.

Application of the results

Map of erosion potential--It was reasoned that sediment production from parts of watersheds with certain characteristics will be the same or proportional to that from whole watersheds with those characteristics. To the degree that this is true, the regression results may be applied to segregate and rate the major source areas of sediment production.

Forest-land erosion potential--The forest land was segregated in 39 complexes with different values of streamflow, topography, or soil variables. Eq. (5) was then solved for each complex, inserting the individual values of the streamflow, topography, and land-use variables and mean (1950) values for the land-use variables. The means used for the land-use variables were 6.1 pct for recent cut-over and 0.1 pct for roads. The calculated suspended sediment production was called the "erosion potential." The individual results for the 39 complexes were grouped to form ten erosion-potential zones for the forest lands. The erosion-potential zones are shown on a map (Fig. 12), with the potential being expressed as average annual suspended sediment production in tons per square mile.

The present sediment production from large forest areas may be expected to be approximately the same as the potential. For small areas where land-use conditions may be far from average, the sediment production expected is the potential times a factor which depends on the deviation of the land use from average. The partial regression coefficients for roads R and recent cut-over RC in (5) permit calculation of this land-use factor, and hence calculation of sediment production.

Agricultural land erosion potential--The regression results, Eq. (6), indicate an average rate of sediment production from cultivated lands of 240 tons per square mile per year. Time was not available to analyze the soil samples which had been taken in the agricultural land soil types to permit determination of their relative erosibility. Therefore another basis of erosibility was used, the Soil Conservation Service Erosion Classes. The erosion classes, 0, 1, 2, and 3, were assigned relative erosion production rates of 0, 1, 4, and 7, respectively, based on the definitions of the respective classes as having top-soil losses of 0, 0-25, 25-75, and greater than 75 pct. The location of these erosion classes are given in Soil Conservation Service Soil and Water Inventory Maps; the relative areas of these four classes in western Oregon were: Class 0, 0.5 pct; Class 1, 67.4 pct; Class 2, 31.7 pct; and Class 3, 0.4 pct. The breakdown of sediment production rates was then: for Class 0, zero; for Class 1, 120 tons/sq mi yr; for Class 2, 480 tons/sq mi yr; and for Class 3, 840 tons/sq mi yr. The location of these agricultural land erosion zones is shown on the erosion potential map (Fig. 12).

The location of eroding banks is not shown on the map, but is given for the Willamette Basin by CORPS OF ENGINEERS [1950].

Major sources of sediment production--The regression results permit segregation of the three major sources of sediment production in the Willamette Basin above Salem, Oregon. Using (6) and the values from Table 6 for sediment production from forest land SSf, for the cultivated land area C and for the length of eroding banks EB, the present average annual sediment production of 1,955,000 tons for the Willamette watershed above Salem may be segregated as follows: from the 5460 sq mi of forest land, 24 pct; from the 1820 sq mi of agricultural land, 22 pct; and from the 205,000 ft of eroding main channel, 54 pct.

Areal limitations of results--The results here reportedly may not always apply to all small local areas. Deviations in sediment production from the estimated potentials will occur where local soil differences occur because of local variation in geology or fault zones, where local slopes are widely different from average for a zone; and where unusual disturbances occur, such as road fills paralleling a stream for long distances, local logging disturbances that are unusually severe, or dam building in process. The map values apply only to the broad erosion potential zones. Differences in the erosion potential between zones indicate the relative need for precautions in land development.

Needs and priorities in further research--Further extensive research of the type of this study is needed to obtain relations between specific criteria of land condition and sediment discharge. For example, the area of bare soil exposed at stream margins and the area of other bare land might be set up as criteria and their values determined for the individual watersheds. If these were included in regression analyses together with the "erosion potential" of the watersheds, an evaluation might result which would permit more effective land management for reduction of sediment discharge from watersheds.

Another need is for estimation of other types or measures of erosion such as surface soil loss and sediment deposition. In studies leading toward such estimations, the methods and some of the variables used in this study should be applicable. For example, in a study of erosion measured as deposition, it is a worthwhile hypothesis that the soil binding variable S/A would be important in its present form, but the supply variable SC should be modified.

Intensive research into economic methods of offsetting adverse effects of land use on sediment production may be justified, especially in those zones where the erosion potential is high. Research priorities suggested by this study are (1) eroding-bank control, (2) road-development methods and precautions, (3) bare-cultivation control, and (4) logging operation methods and precautions.

Summary and conclusions

(1) Suspended sediment sampling results were used to obtain average annual suspended-sediment discharge from 29 watersheds of western Oregon by relation of sediment to streamflow and by use of streamflow frequencies.

(2) Average annual suspended-sediment discharge of watersheds varied from as little as 12 to as much as 840 ton/sq mi.

(3) The variation in sediment discharge was associated with differences in streamflow, topography, soils, bank conditions, and land use, which were numerically evaluated by multiple regression to permit estimation of their independent effects on sediment discharge. The effects may be illustrated by these results: (a) The watershed with the greatest annual streamflow would be expected to have a sediment discharge 11.6 times that of the watershed with the least flow. Similarly, the watershed whose flows were most peaked would have a sediment discharge 3.7 times that of the watershed with the least peaked flows. (b) The watershed with the steepest slopes, as characterized by the slope of the streams of one mile length, would have sediment discharge 2.2 times that

of the watershed with the least slope. (c) Sediment-discharge differences associated with differences in the soil developed on the 14 major geologic types of the mountain areas were significant. The most erosible soil, that developed on Eocene volcanic, was 11 times as erosible as the soil developed on alluvium. (d) If under future development of forest lands, using present methods, the recent cut-over area should occupy 1.5 pct of the watershed area, and roads 0.55 pct, suspended-sediment discharge would be expected to be three times as great as at present. Most of this increase would be associated with the extension of the road area. Conversion of bare cultivated land to other types of cultivation would largely eliminate these lands as sources of suspended sediment. Prevention of bank cutting in the main channels of the Willamette River and tributaries would eliminate 54 pct of the present sediment discharge.

(4) As an aid to land and water managers in planning resource development, a map of the erosion potential of western Oregon was prepared, with erosion potential being defined as the expected annual suspended-sediment discharge if all lands, both forest and agricultural, were in the average 1950 land-use condition.

(5) It is concluded that in the areas of high erosion potential extra precautions should be taken in land-use development, that erosion potential zones should be considered in assigning priorities of research in methods of offsetting adverse effects of land use, and that intensive investigation should be made into methods of controlling sediment production from eroding channel banks, roads, bare cultivated, and logged areas.

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ELASTIC WAVES IN ARCTIC PACK ICE

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Abstract--Elastic wave propagation was studied in the Arctic ice pack, on the Beaufort Sea, the Arctic Ocean, and at near-shore locations. Ice thicknesses varied from 0.9 to 2.1 meters and water depths from 1 1/2 to 3800 meters. Values of the elastic constants were derived from the measured velocities of the longitudinal and shear waves and the density. Dispersive flexural waves and air-coupled flexural waves were examined in detail and were used to deduce ice thicknesses. A high-frequency arrival with a velocity of 1700 meters/second was detected, the theoretical justification of which is not yet determined.

Introduction--During the springs of 1950 and 1951 experimental studies of the propagation of elastic waves in Arctic ice were made on the Beaufort Sea near Barter Island, Alaska. During the summer of 1952 additional data was obtained on the Arctic Ocean near T-3, the ice island floating near the North Pole.

Most of the 1950 work was conducted on shore-fast ice, but helicopter landings were made at three offshore points from 150 - 200 km north of Barter Island shown in Table 1. The 1951 program included studies on the shore-fast ice, on Akvakniakvik Lagoon, a shallow bay east of Barter Island, and at six different sites on the Arctic ice pack proper. The latter were all in deep water and were reached by a ski-equipped Air Force C-47 transport plane. The locations are also shown in Table 1. Oceanographic and meteorologic results from these ice pack stations have been reported in another paper [CRARY, COTELL, and OLIVER, 1952].

Table 1--Points of aircraft landings

Site	Date	Approximate location				Water depth
		°	′ N	°	′ W	m
	1950					
. . .	May 13	71	40	143	37	Not obtained
. . .	May 16	71	20	143	37	1835
. . .	May 23	71	53	143	37	2890
	1951					
A	Apr. 8	74	46	144	55	3750
B	Apr. 10	74	47	138	40	3520
C	Apr. 17	74	45	150	55	3838
D	Apr. 20	73	22	141	20	3457
E	Apr. 22	75	53	142	10	3739
F	Apr. 23	73	11	146	05	3632
	1952					
T-3	. . .	88	. .	110	. .	3000

The shore-fast ice extended to the main pressure ridge from three to six kilometers north of Barter Island, beyond which open leads were occasionally formed. The average ice thickness was about two meters. Water depth varied from 1.5 meters to about three meters. Shore-fast ice in this area freezes each fall and thaws in late spring or early summer so it is never more than one year old. The surface was, in general, rough with relief in the neighborhood of one meter due to disturbance during freezing. Occasionally smooth patches were encountered with linear dimensions ranging up to a hundred meters.

The ice on Akvakniakvik Lagoon, undisturbed during freezing, was smooth and uniform. The depth of the water was about one meter.

The plane landings on the pack ice were made perforce on relatively young ice that had a very smooth surface. Time and transportation difficulties limited the ice pack experiments to this young ice and to adjacent areas of somewhat older and thicker ice. Snow cover was usually slight, less than ten centimeters on the smooth ice though drifts up to a half meter frequently occurred on the rough ice.

All helicopter landings were made near open leads and all were on young thin ice. Wave studies were conducted at only one of the helicopter locations.

The observations near the ice island were taken in early July, 1952, in conjunction with the work being carried out on the island itself. The ice was an old floe approximately 125 by 600 m, with a fairly smooth surface over which several large water puddles were scattered. The water content was probably fairly high. The location was in the vicinity of 88°N, 110°W. Elastic wave studies on the island will be reported in a later paper.

At all sites, holes were bored in the ice using an ice auger for a small three-inch-diameter hole or an ice chisel for a larger hole. On boring the hole it was apparent that the elastic properties of the ice must vary somewhat with depth. The ice making up the upper one-half to two-thirds of the total thickness was dry and hard. However, as one approached the bottom, a gradual increase in water content became evident. Near the bottom the ice appeared soft and wet, and the cuttings slushy. The bottom surface of the ice was frequently a mass of needlelike and lathlike crystals up to 20 cm in length and was very irregular. It thus seems unlikely that any theoretical wave study or experimental technique assuming this surface to be a plane boundary would prove valid for wavelengths of the order of 20 cm.

Equipment and method--A method similar to the seismic-refraction technique was employed for the wave studies. Instruments were aligned at suitable intervals and shots fired at various distances on the prolongation of this line. The size of the shots varied from a detonator to 40 lb of TNT. The majority of the listening devices were portable horizontal and vertical seismometers manufactured by the Stanley Aviation Corp. and designed originally by the Department of Terrestrial Magnetism, Carnegie Institution of Washington. The natural frequency of these seismometers was about two cycles per second. This was also the low frequency cut-off determined by the amplifier-seismometer system. Occasionally, a three-second period, vertical seismometer, designed and built by Columbia University, was used. Carbon button microphones and hydrophones detected the air and water disturbances. Century Geophysical Corp. geophones and amplifiers were used in 1952. Nearly all the recordings were made with a Heiland, 12-channel, photographic oscillograph at paper speeds of three to 24 in/sec. The high-frequency limit of the system was imposed by the oscillograph and amplifiers and was about 200 cycles. Timing lines were placed on the record by a vibrating reed which was periodically checked with a rated chronometer. In most cases, the shot instant was obtained by observing electrically the breaking time of a wire wrapped around the charge. Occasionally, when it was impossible to lay a connecting wire between shot and recorder, the air wave or water wave indicated the time of firing.

Theory--EWING and CRARY [1934] found flexural waves in thin lake ice showing marked dispersion. They developed formulas for phase and group velocities using the equations of motion of a thin plate and taking into account the effect of gravity and the depth of water to a rigid bottom. They found

$$c^2 = (F/\lambda^2 + G\lambda^2)/[\rho + (D\lambda/\alpha)\ \coth(H\alpha/\lambda)] \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

and

$$U = c\left[1 + \frac{2(F - G\lambda^4)\, c_w^2 \alpha^3 \sinh^2(H\alpha/\lambda) + D c^2 c_w^2 \lambda^3 \alpha^2 \sinh(H\alpha/\lambda)\cosh(H\alpha/\lambda) + H\alpha/\lambda}{2(F + G\lambda^4)\, c_w^2 \alpha^3 \sinh^2(H\alpha/\lambda) + D c^4 \lambda^3 \sinh(H\alpha/\lambda)\cosh(H\alpha/\lambda) + H\alpha/\lambda}\right] \quad \ldots\ldots (2)$$

where c = phase velocity
U = group velocity
$F = 1/3\pi^2\, e^2\, \rho\, V_p^2$
$G = g\,\rho_1/4\pi^2\, e$
$\alpha = (1 - c^2/c_w^2)^{1/2}$
$D = \rho_1/2\pi e$
$H = 2\pi h$

λ = wavelength in ice
e = thickness of the ice
h = depth of water below the ice
c_w = velocity of compressional waves in water
V_p = plate velocity of longitudinal waves in ice
g = acceleration of gravity
ρ = density of ice
ρ_1 = density of water

They also showed that

$$V_p = [E/\rho\,(1 - \sigma^2)]^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

where E = Youngs' Modulus and σ = Poisson's ratio.

More recently, PRESS and EWING [1951a] worked out a more complete solution assuming a finite layer of ice overlying a semi-infinite body of water. Their dispersion formulas relating phase velocity and frequency are closely related to those of OSBORNE and HART [1945], who considered the problem of a steel plate surrounded by an infinite body of water. The period equation of Press and Ewing is

$$S\,[a + \delta \cosh(\xi e/2) \cosh(\eta e/2)] + a\,[S + \delta \sinh(\xi e/2) \sinh(\eta e/2)] = 0 \quad \ldots\ldots \text{(4)}$$

where $S = (\eta^2 + K^2)^2 \cosh(\xi e/2) \sinh(\eta e/2) - 4\,\xi\,\eta\,K^2 \sinh(\xi e/2) \cosh(\eta e/2)$
$a = (\eta^2 + K^2)^2 \sinh(\xi e/2) \cosh(\eta e/2) - 4\,\xi\,\eta\,K^2 \cosh(\xi e/2) \sinh(\eta e/2)$
$\delta = (\rho_1/\rho)\, c_w^2/\beta^2\, \zeta(\zeta^2 - K^2)\,(\eta^2 - K^2)\xi$
$\xi^2 = K^2\,(1 - c^2/\alpha^2)$
$\eta^2 = K^2\,(1 - c^2/\beta^2)$
$\zeta^2 = K^2\,(1 - c^2/c_w^2)$

and where α = compressional wave velocity in ice (infinitely extended solid)
β = shear wave velocity in ice
c_w = compressional wave velocity in water
$K = 2\pi/\lambda$
e = ice thickness

Assuming the depth of water to be infinite, it may be shown that for wavelengths that are long compared to the thickness of the ice (4) is identical to (1) with the exception of the gravity term in (1). No gravitational effect was considered in the derivation of (4). The effect of the gravity term is appreciable only at very low frequencies and is small throughout the range covered in these experiments. The deviation of (1) does not depend on the assumption that $\sigma = 0.25$. For shorter wavelengths, (4) diverges from (1) and the group velocity has a maximum for $K\,e/2 \cong 1.3$.

From studies conducted on Lake Superior ice of about 0.5 meter thickness, PRESS and Others [1951] reported an air-coupled flexural wave for explosive sources in the air or near the surface of the ice. To explain this, PRESS and EWING [1951b] added a term, corresponding to the effect of the atmosphere, to the Ewing-Crary derivation of (1). They published phase and group velocity and amplitude curves for this case. For a shot in the water the effect of the atmosphere is negligible and the dispersed train of flexural waves given by (1) and (2) is observed. For a shot in the air or near the surface of the ice, the train is modified by a constant frequency arrival preceding the air wave and arriving over a time interval $\Delta T = X\,(1/V_m - 1/V_a)$, where V_a is the velocity of compressional waves in air and also the phase velocity of the frequency of the air-coupled wave. V_m is the group velocity corresponding to this phase velocity. If the elastic constants and the density of the ice sheet are known, this air-coupled frequency has a simple relation to the ice thickness, that is, $e = A/f$, where e is the thickness, f the frequency, and A a constant determined by the elastic properties.

In Figure 1 is shown the theoretical flexural-wave dispersion for both the layer and plate formulas, for α = 2740 m/sec and β = 1460 m/sec. The gravity term in (1) has been neglected in order to make the velocity a function of ke/2. Also shown in the figure are the air-coupling effects.

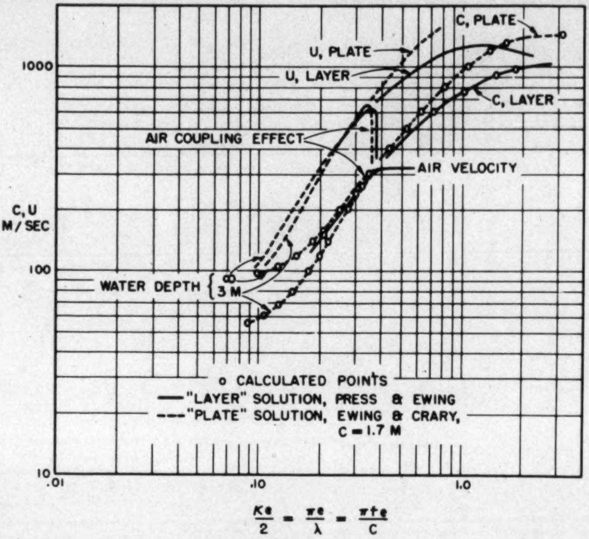
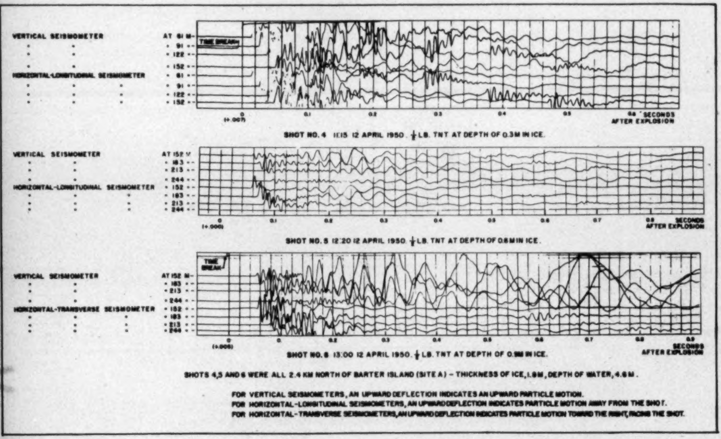


Fig. 1--Theoretical dispersion curves



SHOT NO. 4 11:15 12 APRIL 1950. ½ LB. TNT AT DEPTH OF 0.3M IN ICE.

SHOT NO. 5 12:20 12 APRIL 1950. ½ LB. TNT AT DEPTH OF 0.6M IN ICE.

SHOT NO. 6 13:00 12 APRIL 1950. ½ LB. TNT AT DEPTH OF 0.9M IN ICE.

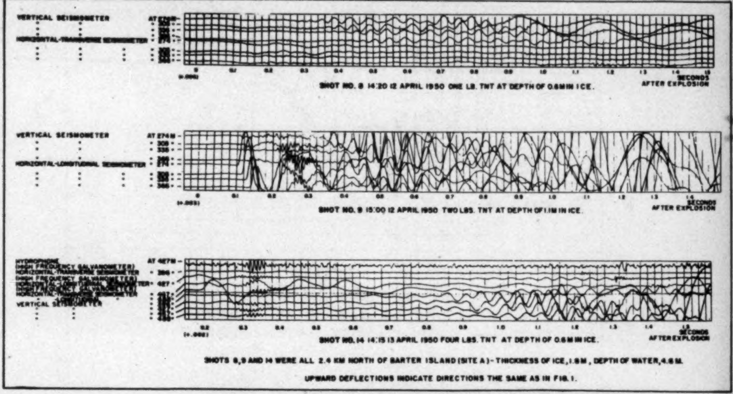
SHOTS 4,5 AND 6 WERE ALL 2.4 KM NORTH OF BARTER ISLAND (SITE A) – THICKNESS OF ICE, 1.8M, DEPTH OF WATER, 4.6M.

FOR VERTICAL SEISMOMETERS, AN UPWARD DEFLECTION INDICATES AN UPWARD PARTICLE MOTION.
FOR HORIZONTAL-LONGITUDINAL SEISMOMETERS, AN UPWARD DEFLECTION INDICATES PARTICLE MOTION AWAY FROM THE SHOT.
FOR HORIZONTAL-TRANSVERSE SEISMOMETERS, AN UPWARD DEFLECTION INDICATES PARTICLE MOTION TOWARD THE RIGHT, FACING THE SHOT.

Fig. 2--Sample profile recordings (Barter Island)

Calculations to determine the magnitude of the effect of a change in density showed this effect to be small for the conditions encountered in these experiments.

Experimental results--Sample recordings obtained near Barter Island, which illustrate various types of elastic waves obtained, are shown in Figures 2, 3, 4, and 5.



SHOT NO. 8 14:20 12 APRIL 1950 ONE LB. TNT AT DEPTH OF 0.8 M IN ICE.

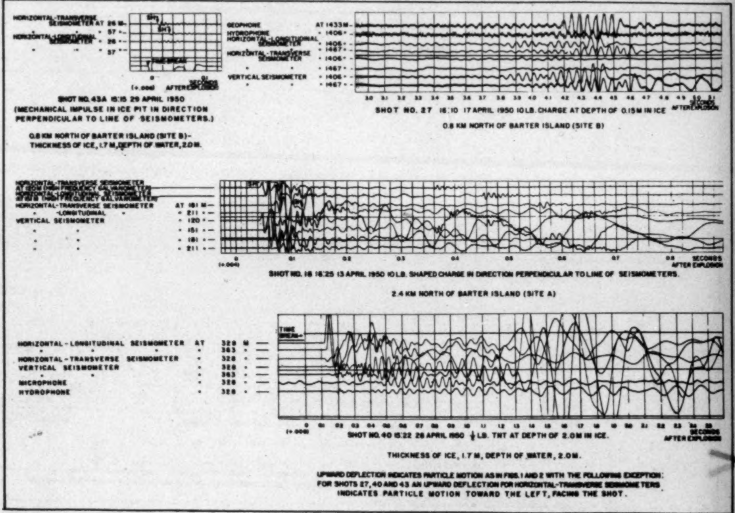
SHOT NO. 9 15:00 12 APRIL 1950 TWO LBS. TNT AT DEPTH OF 1.1 M IN ICE.

SHOT NO. 14 14:15 13 APRIL 1950 FOUR LBS. TNT AT DEPTH OF 0.6 M IN ICE.

SHOTS 8, 9 AND 14 WERE ALL 2.4 KM NORTH OF BARTER ISLAND (SITE A) - THICKNESS OF ICE, 1.8 M, DEPTH OF WATER, 4.6 M.

UPWARD DEFLECTIONS INDICATE DIRECTIONS THE SAME AS IN FIG. 1.

Fig. 3--Sample profile recordings (Barter Island)



SHOT NO. 43A 15:15 29 APRIL 1950
(MECHANICAL IMPULSE IN ICE PIT IN DIRECTION PERPENDICULAR TO LINE OF SEISMOMETERS.)

0.8 KM NORTH OF BARTER ISLAND (SITE B)-
THICKNESS OF ICE, 1.7 M, DEPTH OF WATER, 2.0 M.

SHOT NO. 27 16:10 17 APRIL 1950 10 LB. CHARGE AT DEPTH OF 0.15 M IN ICE

0.8 KM NORTH OF BARTER ISLAND (SITE B)

SHOT NO. 16 16:25 13 APRIL 1950 10 LB. SHAPED CHARGE IN DIRECTION PERPENDICULAR TO LINE OF SEISMOMETERS.

2.4 KM NORTH OF BARTER ISLAND (SITE A)

SHOT NO. 40 15:22 26 APRIL 1950 $\frac{1}{2}$ LB. TNT AT DEPTH OF 2.0 M IN ICE.

THICKNESS OF ICE, 1.7 M, DEPTH OF WATER, 2.0 M.

UPWARD DEFLECTION INDICATES PARTICLE MOTION AS IN FIGS. 1 AND 2 WITH THE FOLLOWING EXCEPTION: FOR SHOTS 27, 40 AND 43 AN UPWARD DEFLECTION FOR HORIZONTAL-TRANSVERSE SEISMOMETERS INDICATES PARTICLE MOTION TOWARD THE LEFT, FACING THE SHOT.

Fig. 4--Sample profile recordings (Barter Island)

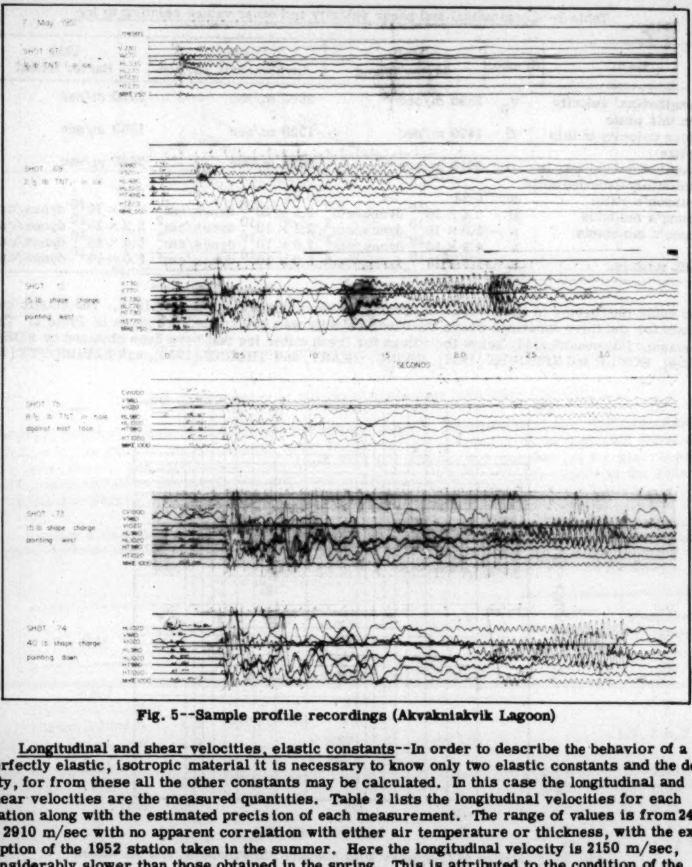


Fig. 5--Sample profile recordings (Akvakniakvik Lagoon)

Longitudinal and shear velocities, elastic constants--In order to describe the behavior of a perfectly elastic, isotropic material it is necessary to know only two elastic constants and the density, for from these all the other constants may be calculated. In this case the longitudinal and shear velocities are the measured quantities. Table 2 lists the longitudinal velocities for each station along with the estimated precision of each measurement. The range of values is from 2400 to 2910 m/sec with no apparent correlation with either air temperature or thickness, with the exception of the 1952 station taken in the summer. Here the longitudinal velocity is 2150 m/sec, considerably slower than those obtained in the spring. This is attributed to the condition of the ice in the summer when melt water permeates a considerable fraction of the total thickness.

Measurement of the shear velocity was somewhat more troublesome because (1) second arrivals cannot be picked with the precision of the initial arrival, and (2) standard explosive sources being non-directional do not, in general, set up transverse waves. To avoid the latter difficulty, determinations were made, though at short distances, by mechanical impact on the side of a deep pit (Fig. 4, shot 43A). Shaped charges were also employed to a limited extent. They were fired in various orientations on the surface, buried in the ice and against the wall of a pit. Although maximum destruction of the ice was highly directional there was little difference between the character of these records and those obtained from non-directional sources under similar conditions, for example, see records 73, 74, and 75, Akvakniakvik Lagoon (Fig. 4). The density of 0.90 gram

Table 2--Longitudinal and shear velocity and other values relating to ice

Item	Symbol	1950 Barter Island	1951 Akvakniakvik Lagoon	1951 Barter Island
Longitudinal velocity in this plate	V_p	2590 m/sec	2600 m/sec	2790 m/sec
Shear velocity in this plate	β	1490 m/sec	1520 m/sec	1560 m/sec
Longitudinal velocity in infinitely extended solid	α	3010 m/sec	2930 m/sec	3490 m/sec
Poisson's ratio	σ	0.34	0.32	0.37
Young's modulus	E	5.4×10^{10} dynes/cm^2	5.5×10^{10} dynes/cm^2	6.0×10^{10} dynes/cm^2
Lame's constants	μ	2.0×10^{10} dynes/cm^2	2.1×10^{10} dynes/cm^2	2.2×10^{10} dynes/cm^2
	λ	4.2×10^{10} dynes/cm^2	3.6×10^{10} dynes/cm^2	6.6×10^{10} dynes/cm^2
Bulk modulus	K	5.5×10^{10} dynes/cm^2	5.0×10^{10} dynes/cm^2	8.0×10^{10} dynes/cm^2

per cubic centimeter is the average of several measurements made during 1951. The elastic constants for the three locations where the shear velocity was determined are given in Table 2. These constants fall considerably below the values for fresh water ice that have been obtained by KOHLER [1924], BOYLE and SPROULE [1931], EWING, CRARY, and THORNE [1934], and KISHINOVYE [1945].

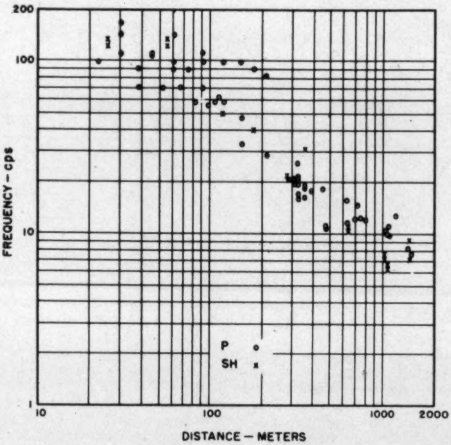


Fig. 6--Variation of frequency with distance, longitudinal, and SH waves

Figure 6 shows the decrease of longitudinal and shear arrivals with distance. This is attributed to more rapid attenuation of the higher frequencies.

Air-coupled waves--Air-coupled waves are very prominent in recordings where the shots are fired at or near the ice surface at distances over about 200 times the ice thickness. The series of records from Akvakniakvik Lagoon shown in Figure 5 illustrate the development of the air-coupled wave quite well. Good air-coupled waves are also shown in Figure 4, Shot 27.

The calculations of ice thicknesses from the recorded frequencies of the air-coupled wave are made from Figure 7, where the constant A = ef is plotted against the plate velocity. In addition to the plate velocity, this air-coupled constant depends also on the air temperature, which determines

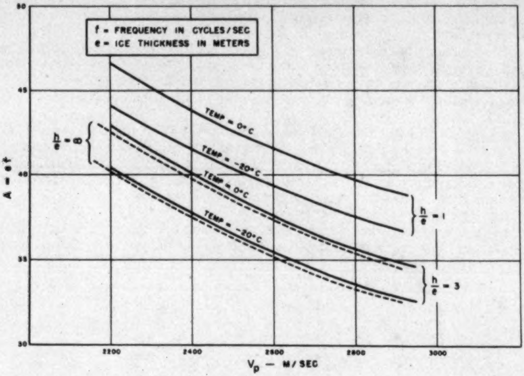


Fig. 7--Variation of air-coupled constant with plate velocity

the air velocity, and the depth of the water, as noted in (1). For practical use, this dependence is shown by the ratio of the water depth to the thickness, and is noted to be insignificant above a ratio of about three. The calculations from which Figure 7 was derived made use of the plate formula, (1). At an infinite water depth, the only case in which (4) is used, the differences in the constant, as noted in Figure 1, is insignificant.

Table 3 lists the measured thicknesses of the various sites compared with the thickness as obtained from the air-coupled wave. It will be noted that in all cases the value obtained by the

Table 3--Data relating to the various sites

Site	Water depth	V_p	Air-coupled frequency	Calculated thickness	Calculated thickness from flex. waves	Measured thickness
	m	m/sec	c/sec	m	m	m
1950						
Helicopter landing	. . .	. . . .	27.4	1.2	. . .	1.2
Barter Island A	4.6	2700 ± 50	21.6	1.6	. . .	1.8
Barter Island B	2.0	. . . .	22.9, 21.6	1.5, 1.6	. . .	1.7, 1.8, 2.1
1951						
A	Deep	2800 ± 200	20.2	1.61	2.0[a]	1.67
B	Deep	2860 ± 50	. . .	. . .	0.8[b]	0.99
C	Deep	2910 ± 100	20.2	1.88	1.0[b]	2.13
D	Deep	2550 ± 50	57.3	0.65	0.7	0.86
E	Deep	2500 ± 50	42.4	0.88	0.8 - 0.9	1.06
F	Deep	2850 ± 50	21.3	1.59	1.4 - 1.5	1.87
Barter Island	1.83	2790 ± 30	19.2	1.77	. . .	1.83, 1.68
Barter Island	2	2400 ± 50	14.2	2.74	. . .	c
Akvakniakvik Lagoon	1	2600 ± 50	24.6	1.54	1.0[b]	1.83
1952						
T-3	Deep	2150 ± 100	24.1	1.95	1.7	2.3

[a] Ice thickness not uniform over path.
[b] Flexural waves jumbled, probably due to lateral reflections.
[c] Very rough ice, no measured values applicable.

air-coupled wave falls below the measured thickness. One difficulty obviously lies in the bore holes. The figure calculated from the air-coupled wave is the thickness of an equivalent homogeneous elastic plate, which, for calculations involving the strength of the ice, for example, the support of a load, would undoubtedly be more suitable. A further difficulty comes from the horizontal variations, even in undeformed ice of the same age. The air-coupled frequency is determined by the average thickness over a substantial area, probably of the order of 100 to 200 times the ice thickness, while all measured thicknesses were made at one site only.

Flexural waves--Flexural waves, which are obtained best by shots in the water directly under the ice sheet, range in frequency throughout the limits imposed by the equipments. Illustrations of these waves are noted in Figures 2, 3, and 4. As most of the shots were made at or near the surface of the ice, the flexural waves are most pronounced either after the arrival of the air wave, or at distances less than needed to develop a good air-coupled wave.

Figure 8 shows the flexural wave dispersion as obtained on the sea ice immediately off Barter Island. The deviation from the plate formula at the low frequencies is probably due to the erroneous assumption of a rigid bottom.

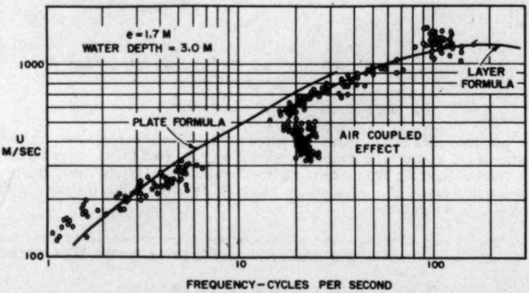


Fig. 8--Observed dispersion of flexural waves (Barter Island)

The number of shots at most ice landings was severely limited by the lack of time. Surveys of the areal extent of various kinds and thicknesses of ice were likewise curtailed. However, considerable information is available from the data as it stands. Site D is described as representative of the procedure and illustrative of both the flexural wave and air-coupled wave techniques.

It is the most complete set of data that was obtained at any location on the ice pack. There were three shot points and a three-instrument spread. All distances were chained and time breaks recorded. The flexural wave dispersion is plotted in Figure 9. It varies with shot distance indicating a change along the path in the elastic properties, or the thickness of the ice, or both. The thickness was measured at only one place, on the thin ice near the middle instrument.

By plotting the first arrival of the longitudinal wave, two velocities can be determined, 2530 m/sec in the thin ice and 2750 m/sec in the thicker ice. The intersection of these travel time segments indicates a break in the character of the ice near shot 1 which was also the location of the first pressure ridge and the termination of the smooth ice. Thus the dispersion for the first shot is due entirely to thin ice. Subtracting this from the dispersion for the longer shots we can get the effect of the thick ice on the train of flexural waves and from this a value for the thickness of the thicker ice, about 2.7 m. As these calculations are sensitive to changes in the group velocity and since relatively few points are available to measure the group velocity curve, the precision of the result is not high. An error of 25 pct might result in this manner.

If only the longest shot had been fired, the flexural wave dispersion would have indicated a thickness of about one meter for the entire path, with no indication of a discontinuity. This is clear proof of the superiority of the air-coupled wave to the flexural wave train for determination of ice thickness in the Arctic, since the air-coupled wave gives the true thickness of the ice near the instrument in the direction of the shot.

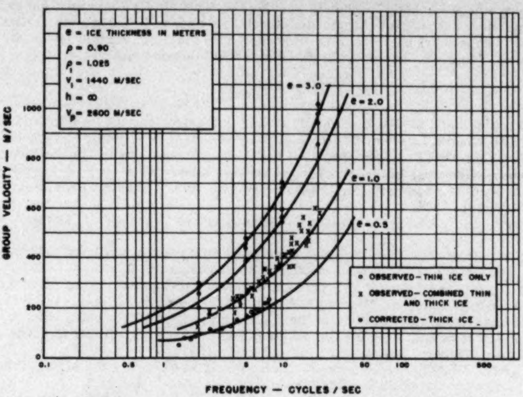


Fig. 9--Observed dispersion of flexural waves (Site D)

POULTER [1950] took records of a similar nature on a bay in the Antarctic. Dispersive trains of flexural waves are evident on his records, 39 - 208, 50 - 242, and 41 - 216. Records 48 - 235 and 50 - 242, both shots on the ice surface, have air-coupled waves with a frequency of about 13 cycles per second preceding the air wave. No velocity is given for longitudinal waves in the thin ice and the records that are published, taken with an emphasis on bottom reflections, are poor for this purpose. Assuming V_p = 2600 m/sec and the other constants as above we get a thickness of 2.8 m (9.2 ft) from the air-coupled wave, somewhat lower than the 4.6 m (15 ft) stated in the report. However, this value was evidently obtained some distance from the stations so may be somewhat inaccurate. There may also be considerable error in the assumed values for the elastic constants. The poor response of the instruments at the flexural wave frequencies makes any values for ice thickness obtained from the dispersion doubtful.

Predominant high frequency group--The Barter Island profiles for both years show a high-frequency arrival somewhat similar in character to the water arrival on other profiles (Fig. 2, 3, 4). However, the velocity in this case is much too high, 1600 - 1700 m/sec as compared to 1440 m/sec for water. The frequency appears to be near and above the upper limit of the instruments. The arrival also appears prominently on a hydrophone located near the ice - water interface. It appears most prominently when the shot is on the surface of the ice or in a dry hole and is detected by transverse, longitudinal, and vertical components.

The method of propagation of this wave is not understood. Poulter attributed an arrival of similar velocity in the Ross Shelf ice to the water-saturated ice layer just above the ice water contract. His reasoning depended upon a time intercept that would be too small to be detected in our case.

The layer solution of Press and Ewing has a group velocity maximum at about 200 cycles per second, but the velocity is only 1300 m/sec. It does not take into account the shallow bottom, which is apparently important here, because the arrival only appears on shallow water shots.

The possibility of a shallow sedimentary layer or a shallow bottom reflection seems unlikely because of the prominence of the arrival from shots on the surface of the ice.

The most fruitful approach to the problem would probably be an investigation of the normal modes propagated in an acoustical system including the ice, water and bottom. Such three-layer calculations are so time consuming that they were not attempted here.

Acknowledgments--Acknowledgments are due the Alaskan Air Command for supplying the necessary facilities and the 10th Air Rescue Service, Squadron D, for transportation to the ice pack stations. The authors also thank Carlton Molineux and T. F. Sexton, of the Air Force Cambridge Research Center for assisting in parts of the field operations.

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SEISMIC STUDIES ON FLETCHER'S ICE ISLAND, T-3

A. P. Crary

Abstract--Seismic studies were made on Fletcher's Ice Island in the Arctic Ocean during June and July, 1952, to determine the thickness and elastic characteristics of this ice body. Two types of seismic profiles were made, one using explosives detonated at or near the surface, and one using mechanical impacts. Compressional and torsional velocities were obtained, as well as good flexural waves at the longer distances. A single shot was fired at the surface at a distance of 5 1/2 miles for the generation of an air-ice coupled wave. In addition to these standard types, a constant frequency multi-reflected SV wave showed unusually large amplitudes at the long distances. The ice thickness was obtained independently by seismic energy reflected from the ocean bottom. The arrival times through the island were compared with arrival times to the surrounding ice pack at sea level. The thicknesses obtained by these various types of measurement are quite consistent, giving from 160 to 170 ft, corresponding to an average density of about 0.91 gms/cm^3, as deduced from the elevations. This value of density was also obtained by direct measurements in the upper 50 ft of ice.

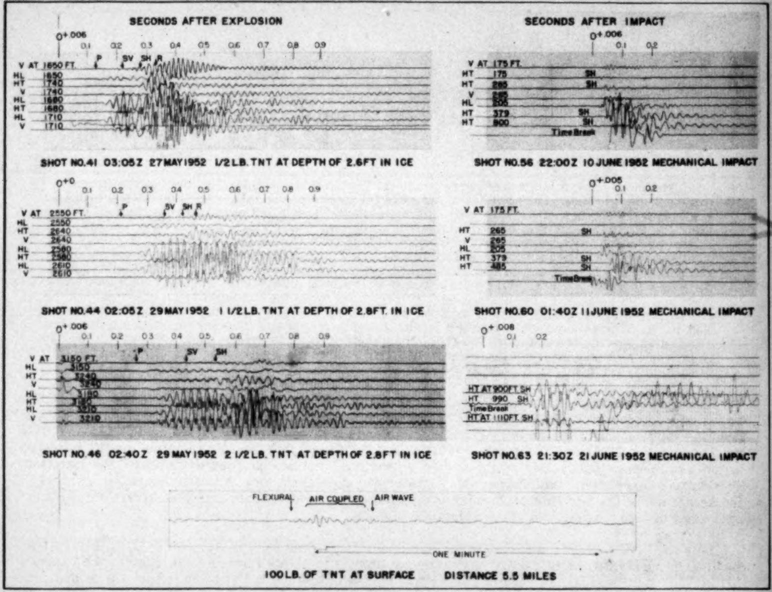
Introduction--The occurrence of large bodies of ice floating in the ice pack of the Arctic Ocean was first reported by FLETCHER [1950], and was discussed in more detail by KOENIG and Others [1952]. The first aircraft landing on these ice islands was made on the island designated as T-3 by the Alaskan Air Command in March, 1952. A party under J. O. Fletcher remained on the island to set up a temporary base. During the period in which the present studies were made, the logistics for this base have been furnished by the Alaskan Air Command. Air Weather Service personnel, and scientists of the Air Research and Development Command, Cambridge Research Center, have conducted meteorological and other scientific studies.

Seismic profiles were made over the surface of the island for two purposes; (1) to determine the elastic constants and thickness of the island, and (2) to obtain further knowledge of the characteristics of plate waves. The island, about five by ten miles and 165 ft thick, offered a unique configuration for such studies.

Experimental procedure--Standard seismic-refraction methods were used with various types of recording equipments. Detectors of the type employed in seismic exploration work, obtained from the Electro-Technical Laboratories, were used for the higher frequency response. These had a general range of 25 - 120 cps and could be used in any orientation. Vertical and horizontal seismometers made by Stanley Aviation Co. were used for the frequency range of about 2 - 100 cps. These detector units were recorded through standard amplifiers to a Heiland photographic oscillograph. A third instrument used was a vertical seismograph with a period adjustable from one to five seconds, designed at the Lamont Geological Observatory. Its output was recorded on an Esterline-Angus ink recorder.

Two types of profiles were made. The principal one made use of high explosives buried in the ice to depths of eight feet. The largest charge used was 100 lb of TNT, and this profile was made to a distance of 17,000 ft. A second type utilized mechanical impulses set up by swinging a 150-lb rock from a 30-ft A-frame against the face of a shallow ice pit. This was used to set up SH waves. The recorders were put out at right angles to the line of impact and aligned to receive these waves.

Results--Figures 1 and 2 show some of the recordings obtained. The discussion that follows takes up separately the various types of waves and the results obtained from each. In the theoretical study of plate waves, as discussed by LAMB [1917] for a plate in a vacuum, and by OSBORNE and HART [1945] for a plate surrounded by water, there are two types: the symmetrical, which includes the solid and plate longitudinal waves and the Rayleigh waves, and the anti-symmetrical type forming the flexural wave. The special study of the plate resting on water was treated originally by EWING and CRARY [1934] and later, in more detail, by PRESS and EWING [1951a]. This case does not resolve itself into the symmetrical and anti-symmetrical types, although the solutions are similar.



SHOT NO.41 03:05Z 27 MAY 1952 1/2 LB. TNT AT DEPTH OF 2.6 FT IN ICE

SHOT NO.56 22:00Z 10 JUNE 1952 MECHANICAL IMPACT

SHOT NO.44 02:05Z 29 MAY 1952 1 1/2 LB. TNT AT DEPTH OF 2.8 FT. IN ICE

SHOT NO.60 01:40Z 11 JUNE 1952 MECHANICAL IMPACT

SHOT NO.46 02:40Z 29 MAY 1952 2 1/2 LB. TNT AT DEPTH OF 2.8 FT IN ICE

SHOT NO.63 21:30Z 21 JUNE 1952 MECHANICAL IMPACT

100 LB. OF TNT AT SURFACE DISTANCE 5.5 MILES

Fig. 1--Samples of recordings

P and SH waves and elastic constants--In the theoretical studies of plate waves, the compressional and torsional wave velocities satisfy the characteristic equations for all frequencies. The P-type waves received in these experiments on the profile where explosive charges were used were of two distinct types. A small-amplitude, high-frequency arrival of 100 - 200 cps was present to about 3000 ft before it became too weak to pick. These times are plotted in Figure 3a. At about 3000 ft, a lower frequency wave of 10 - 20 cps began to appear on the record at a time corresponding to the approximate P wave arrival. This is noted in the time-distance curves in Figure 3b. It is assumed that this is the longitudinal plate wave which is generally about 0.9 the velocity for an infinite solid.

The SH wave was obtained by the mechanical means described above, recording along a line at right angles to the direction of impact, with the horizontal detectors aligned at right angles to the profile. Good picks were obtained only to about 1000 ft. With explosive sources there should be no SH wave developed, because there would ordinarily be horizontal symmetry. However, as noted on nearly all the records and as shown in Figure 3b, a fairly good impulse, appearing only on the components oriented in the SH alignment and with the approximate SH velocity as determined by the impact studies, is present. The only explanation offered for the appearance of these waves is possible non-symmetry of the source. It is noted that the direction of break and the general characteristics are not consistent.

In Figure 3a an increase in both velocity types is noted near 300 ft, the P wave increasing from 11,000 ft/sec to 12,400 ft/sec and the SH wave increasing from about 5600 ft/sec to 6040 ft/sec, though the latter is not well defined. The change in the P-wave velocity corresponds to a small change in elastic constants at a depth of about 50 ft.

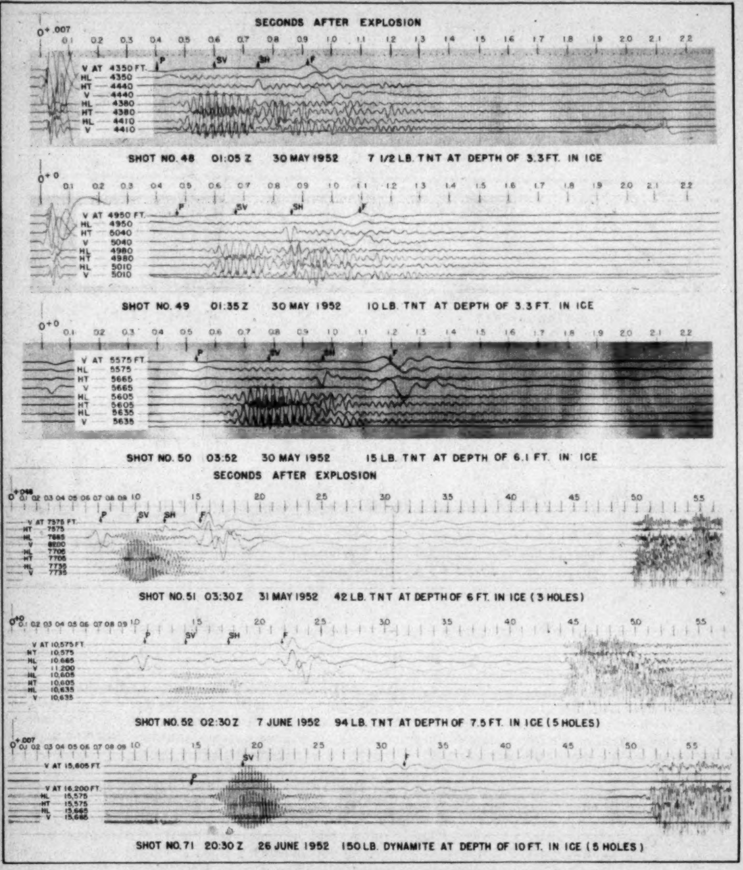


Fig. 2--Samples of recordings

The density of ice was measured by the immersion method on 29 cores taken from a 52-ft hole drilled near the campsite about 2000 ft from the seismic profile. The density values varied from 0.880 to 0.919 gm/cm^3 and averaged 0.907 gm/cm^3 with a small irregular increase with depth. Table 1 shows the approximate constants above and below 50 ft. In the calculations made below, the constants obtained below 50 ft have been used.

Flexural waves--The flexural waves for a floating ice sheet were fully treated by PRESS and EWING [1951a]. The flexural waves obtained in this case included those with the maximum group velocity. Figure 4 shows the theoretical curves for phase and group velocities using the constants

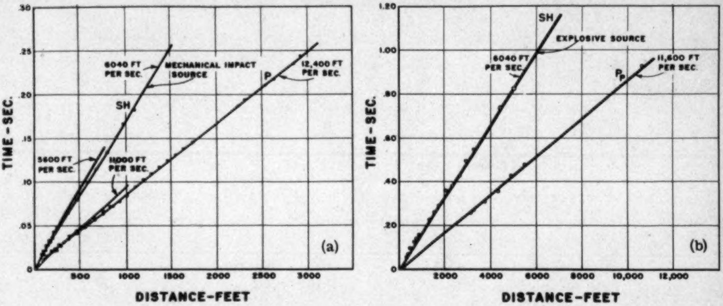


Fig. 3--Relationship of time to distance, seismic profiles (a) 100 to 200 cps; (b) 10 to 20 cps

Table 1--Values of constants determined

Constant	Above 50 ft	Below 50 ft
α, compressional wave velocity (solid)	11,000 ft/sec (3,353 m/sec)	12,400 ft/sec (3,780 m/sec)
β, torsional velocity	5,600 ft/sec (1,707 m/sec)	6,040 ft/sec (1,841 m/sec)
σ, Poisson's ratio	0.325	0.345
E, Young's Modulus	7.0×10^{10} dynes/cm^2	8.5×10^{10} dynes/cm^2
μ, shear modulus	2.6×10^{10} dynes/cm^2	3.1×10^{10} dynes/cm^2
K, bulk modulus	6.7×10^{10} dynes/cm^2	9.1×10^{10} dynes/cm^2
λ	4.9×10^{10} dynes/cm^2	7.0×10^{10} dynes/cm^2

obtained for the ice. From a comparison with the recordings, it is noted that this group velocity maximum is very prominent and both higher and lower frequencies occur with decreasing velocities. The determination of the frequency having maximum velocity gives at once the thickness of the ice, using constants taken from the theoretical curve, and in this case we get a value of about 164 ft, with an accuracy of about ten feet. Figure 5 shows the flexural waves obtained compared to the theoretical curve for a plate of this thickness. In Figure 6, a sample time-wave number plot is shown for these flexural waves.

Air-ice coupled wave--Closely allied to the flexural wave is the air-coupled wave discussed by PRESS and Others [1951], and PRESS and EWING [1951b]. The frequency of this wave is that of a flexural wave having a phase velocity equal to the sound velocity in air. It is generally obtained with explosive shots fired on or above the surface of the plate. Figure 1 shows the air-coupled wave obtained 5 1/2 miles from a shot of 100 lb of TNT fired at the ice surface. From Figure 6 a constant frequency of 0.66 cps is indicated. From Figure 4 we find that the thickness should be $H = 109.5/f$, so that a value of 166 ft is obtained by this means.

Multi-reflected SV wave--An unusual type of SV wave was received with large amplitudes on the long-distance records and is present on nearly all recordings over about 2000 ft. This is a very nearly constant frequency wave intermediate in arrival time between the P and the SH waves. It is most prominent on the horizontal seismograph in line with the profile, although it is present with smaller amplitudes on the vertical seismograph. A small amount of dispersion is present, the frequency increasing very slightly with time, as noted in Figure 6. The phase velocity as determined from shot 71 over a 90-ft spacing is 11,000 to 12,000 ft/sec.

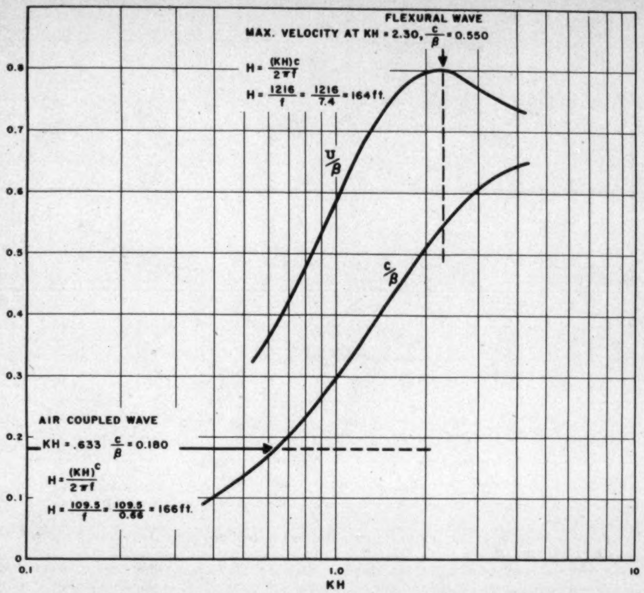


Fig. 4--Theoretical curves for phase and group velocities, ice over water

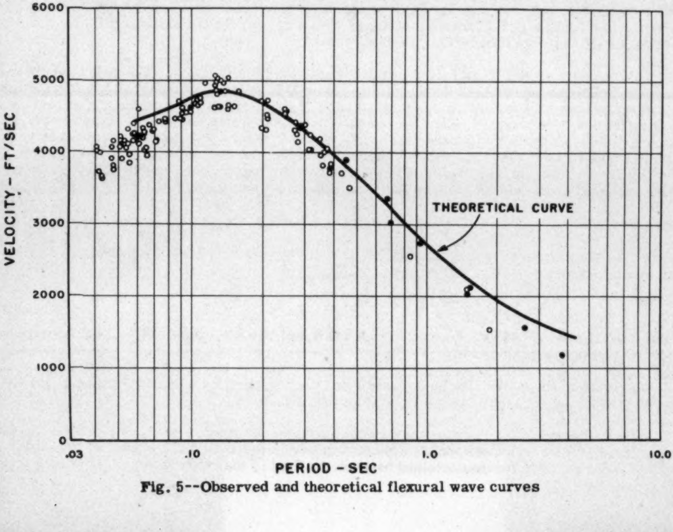


Fig. 5--Observed and theoretical flexural wave curves

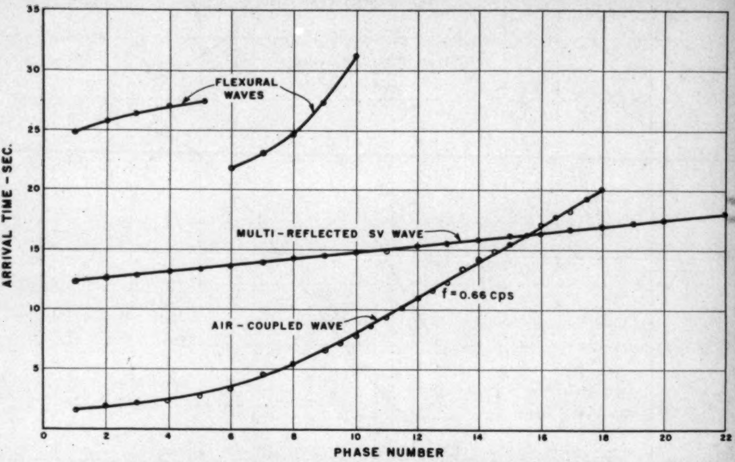


Fig. 6--Observed arrival time-wave number relationships

The calculations of energy ratios from reflections incident at the free surface, such as made by JEFFREYS [1926], and at a solid-liquid interface, such as made by ERGIN [1952], have been repeated with the constants for ice, in which Poisson's ratio is somewhat higher than the values encountered in the Earth. These curves are shown in Figure 7. It is noted that only the SV wave arriving at either interface with an incident angle θ, given by $\theta = \sin^{-1} \beta/\alpha$, is totally reflected back into the ice, and in both cases is reflected in its original form as an SV wave. At this particular angle the vertical displacement becomes zero. The horizontal displacement becomes unusually large, as pointed out by GUTENBERG [1944].

Following the method outlined by PRESS and EWING [1951a], we can derive a formula relating this SV wave frequency to the thickness of the ice by finding the frequency that gives constructive interference between the multiply reflected waves. For the incidence angle of the SV wave giving total reflection, a reversal of phase is present at both the air-ice and the ice-water interface. Also, as noted in Figure 8, the phase velocity is $\beta/\sin\theta$, where β is the torsional wave velocity. As noted above, the phase velocity determined from the records was 11,000 to 12,000 ft/sec. The requirement for constructive interference is that the length of the path ABCD, corrected for phase shifts at the interfaces, will be some multiple of a wavelength, or

$$2H \cos\theta - L = n\, L$$

where L is the wavelength along the path ABCD which equals β/f, f being the frequency. The equation above becomes

$$H = \beta/(f \cos\theta) \qquad \text{for } n = 1$$

In our case, where $\alpha = 12{,}400$ ft/sec and $\beta = 6{,}040$ ft/sec, we have $H = 6920/f$. Thus for a frequency of 40 cps, this gives a thickness of 173 ft.

The equation above can also be obtained from the characteristic equation given by PRESS and EWING [1951a], by setting the phase velocity, c, equal to α.

Reflection through Ice Island from the ocean bottom--In order to obtain an independent means of measuring the ice thickness, small explosions made in the water off the edge of the island were used, with a direct comparison obtained between the time of the reflected ray that passed through

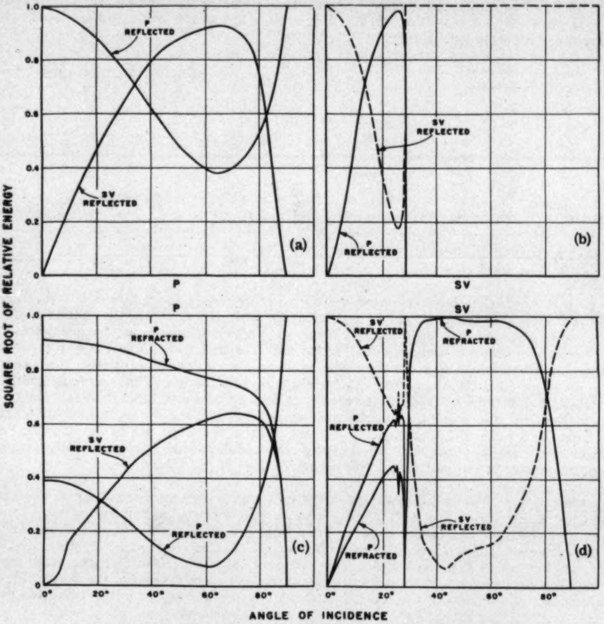


Fig. 7--Reflections and refractions at interfaces, (a) and (b) incident at free surface, (c) and (d) incident at ice-water interface

the island ice and the time of the reflected wave arriving at sea level near the source. Since the velocity in the ice is about 2.6 times that in the salt water, and the resolution of the received time is 0.001 second, an accuracy of about eight feet can be obtained. A time was chosen when the ocean bottom was very flat as evidenced by bottom reflections to seismic spreads on the pack ice. The depth was about 10,800 ft. Since the velocity of the salt water is well known, the time correction for various distances from the source could be calculated with the required accuracy.

Six locations were measured, ranging from 1000 to 3000 ft from the edge of the island. Table 2 lists the results obtained and the method of calculation. Corresponding density values are those

Table 2--Results of observations to determine ice thickness by bottom reflections

Position	Distance from source	T_{calc}	T_{obs}	$T_c - T_o$	Thickness	Elevation	Density
	ft	sec	sec	sec	ft	ft	gm/cm^3
1	1195	0.0068	-0.0070	0.0138	131	16.2	0.89
2	1615	0.0125	-0.0020	0.0145	132	14.1	0.92
3	2210	0.0234	0.0070	0.0164	161	22.8	0.88
4	2514	0.0302	0.0135	0.0167	147	12.7	0.93
5	2735	0.0358	0.0190	0.0168	145	10.9	0.95
6	3074	0.0452	0.0280	0.0172	162	19.9	0.90

needed for isolated equilibrium. Figure 9 shows the general profile obtained. The location of Station 6 was about 2000 ft from the refraction profile, and was the same as the instrument location for the air-ice coupled wave test.

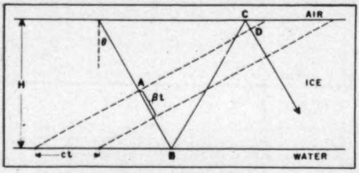


Fig. 8--Ray-path diagram of SH waves in an ice sheet on water

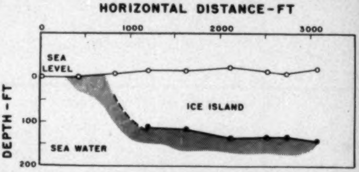


Fig. 9--Profile of Ice-Island edge

Density and ice thickness--It is noted in Table 2 that, except for the deep trough, the densities in general correspond to those measured in the deep core hole. Over the refraction profile, the elevations varied from 17 to 22 ft above sea level. Elevations along the entire path of the air-coupled shot were not measured but, considering that only the last part of the travel path would be effective, the elevations would be about the same as along the refraction profiles. The overall check of density, elevation, and thickness for equilibrium confirms the use of the various seismic wave studies. OLIVER and Others [1954] have noted a difference in the thickness of salt ice as determined by the flexural waves and by direct measurement. In the earlier work of PRESS and Others [1951] on fresh-water ice, this discrepancy was not present, perhaps due to the sharper boundary at the bottom of the fresh-water ice. The results obtained here would seem to indicate that there is little encroachment of the salt water into the lower part of the island ice.

Acknowledgments--Personnel from the Air Force Cambridge Research Center assisting in various phases of the work were R. D. Cotell, who worked with the author during most of the field operations; T. F. Sexton, who assisted in the later field operations which included the air-coupled shot and the reflection studies from the ocean bottom; F. T. Crowley and A. Epstein, who computed necessary data for use in Figures 7 and 4, respectively; and V. C. Bushnell, who made many of the computations and prepared the final graphs. The author also acknowledges the helpful discussions with Frank Press, of the Lamont Geological Observatory, regarding the multi-reflected SV wave.

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DATING GALENAS BY MEANS OF THEIR ISOTOPIC CONSTITUTIONS

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Abstract--A number of isotopic analyses of ore leads from Precambrian deposits have been made. These leads have been classed as "ordinary" or "anomalous" on the basis of their isotopic compositions. The authors suggest that ordinary leads may be dated by comparing their isotopic abundances with average lead abundance-time curves provided that a possible error is assigned which is sufficiently large to include the effects of irregularities of the uranium, thorium, and lead distribution in the Earth's crust. These errors have been calculated for two Earth models which seem physically reasonable. In both cases the errors are sufficiently small for all Precambrian specimens so that the ages may be useful. For early Precambrian samples the errors are comparable to those for standard radioactive age determinations. Galenas which have been dated in this way give ages which seem reasonable in view of their geological environment.

The anomalous type of ore leads can be explained by large additions of radiogenic lead to ordinary lead, and the lead abundance ratios can be used in a least-squares calculation to provide a limit to the time of separation of the leads from the source of the radiogenic additions. This method is applied to a suite of samples from the Sudbury, Ontario, area.

Introduction--It is well known that the variations in the isotopic abundances of ore leads cover a much greater range than could possibly be explained by simple isotopic fractionation during any natural physical or chemical process. The observed abundances can be explained by additions of different quantities of those lead isotopes produced by the radioactive decay of uranium and thorium. It is here assumed that variations of the lead isotopes found in galenas are due entirely to this effect.

We recognize two distinct classes of common leads which may be distinguished by means of their isotopic abundances. These will be referred to as "ordinary" and "anomalous" leads. Most leads for which isotopic analyses have been reported are ordinary leads. They have been used by HOLMES [1946], and by BULLARD and STANLEY [1949] to calculate the age of the Earth's crust, and can be fitted reasonably well to the average lead abundance curves suggested by ALPHER and HERMAN [1951], and recently recalculated by COLLINS and Others [1953]. The anomalous leads cannot be fitted to the average lead abundance curves and cannot be used in Bullard's calculations. They are characterized by very high Pb^{206} and Pb^{208} abundances. As far as is known there is a sharp division between the anomalous and ordinary leads, there being no samples known to the authors which cannot be easily classified in one of the two divisions.

This paper attempts to interpret the abundances of both the ordinary and anomalous leads in a quantitative manner. In particular, formulas are developed which can be used to predict the possible errors associated with ages obtained for ordinary leads by using the average lead abundance curves. The authors postulate that the anomalous leads result from the addition of radiogenic lead to ordinary leads during some exposure to a much higher concentration of uranium and thorium than is commonly found in the material of the Earth's crust. A method of estimating the time of addition of the radiogenic component is suggested.

These formulas are applied to some lead isotope abundances reported by NIER [1938] and by NIER and Others [1941] as well as to a number of new analyses made in this laboratory. The isotopic analyses of a calibration sample supplied by R. S. Cannon and L. R. Stieff of the United States Geological Survey are included in order that the abundances of the samples reported can be compared with analyses which may be carried out at other laboratories.

Methods of calculation--The fundamental formula for any radioactive decay can be written

$$-dN = \lambda N dt$$

where $-dN$ is the small decrement of the number of atoms N of the decaying element in time dt, and λ is the decay constant for that element. Applying this to the decay of U^{235} and noting that the number of parent atoms that decay must be identically equal to the number of radiogenic Pb^{207} atoms, $N(Pb^{207})$, that are formed, we obtain

$$dN(Pb^{207}) = \lambda N(U^{235}) e^{\lambda t} dt$$

where $N(U^{235})$ is the number of atoms of U^{235} remaining at the present time ($t = 0$) and hence $N(U^{235}) e^{\lambda t}$ is the number present t years ago. If we divide through by $N(Pb^{204})$ and put $x = N(Pb^{207})/N(Pb^{204})$ and $V = N(U^{235})/N(Pb^{204})$, this last equation reduces to

$$dx = \lambda V e^{\lambda t} dt \quad \ldots\ldots\ldots\ldots \quad (1)$$

If it can be assumed that uranium, thorium, and lead were uniformly distributed throughout the crust when it solidified, and that subsequent processes caused only small deviations from the original uniform distribution (except in the case of actual mineral deposits), then V is a constant. In this instance integration of (1) leads directly to the type of formula used by Alpher and Herman and by Collins and Others to determine the relationship between the average abundances of ore leads with the time of separation of the leads from the parent magma. Figure 1, which is reproduced from COLLINS and Others [1953], shows this relationship graphically.

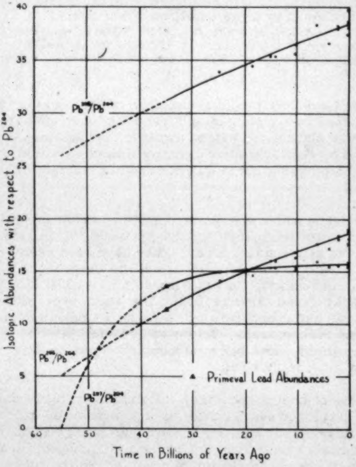

Fig. 1--The variation in isotopic constitution of ore leads with time of formation

However, the fact that the Earth's crust is not homogeneous and the fact that the observed lead isotope abundances do not fit exactly on the average abundance curves show clearly that the uranium/lead and thorium/lead ratios are not everywhere the same. Thus V is not constant. However, we may consider an average value, $\overline{V}$, and say that V always lies somewhere within the limits $\overline{V} \pm \delta V$, where δV is the maximum deviation from the average value. δV may be a function of time, for the maximum deviation of the uranium/lead ratio may not have been the same at all times during the history of the Earth.

Eq. (1) can be formally integrated without assuming that V is constant.

$$x = x_o + \int_t^T \lambda V e^{\lambda t} dt \quad \ldots\ldots \quad (2)$$

The maximum deviation in x at time t resulting from the fact that V is not constant can be obtained by taking the differential of (2) while holding t constant.

$$\delta x = \int_t^T \lambda \delta V e^{\lambda t} dt \quad \ldots\ldots \quad (3)$$

Eq. (3) can also be obtained by calculating the amount of Pb^{207} generated between the time at which the Earth ceased to be homogeneous, T, and the time of separation of the lead mineral from the crust, t, by the amount of U^{235} represented by δV.

Eq. (3) gives the spread in Pb^{207} abundances which would be produced at any time by the maximum deviation in the uranium/lead values. However, for dating ores by lead isotope abundances the spread in abundances at a given time is not nearly as interesting as the spread in time expected for a particular abundance. This can also be obtained by calculating the differential of (2), this time holding x constant.

$$0 = -\lambda \overline{V} e^{\lambda t} (\delta t) + \int_t^T (\delta V) \lambda e^{\lambda t} dt$$

$$\delta t = (1/\lambda \overline{V})\, e^{-\lambda t} \int_t^T (\delta V)\, \lambda\, e^{\lambda t}\, dt \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Neither (3) nor (4) can be used for numerical calculations unless some analytical expression is postulated for δV. In an attempt to determine the form of δV we have assumed that at time T the Earth was homogeneous and δV was zero. At the present time ($t = 0$) δV has some positive value, for the Earth's crust is certainly not homogeneous. Since we cannot visualize any likely process whereby the Earth would become first more heterogeneous and then later become more homogeneous, it seems safe to say that δV can never increase with increasing t. Furthermore, it seems reasonable to suppose that if the Earth's crust were changing more rapidly during a part of its history, the rate of change would be greatest during solidification and shortly afterward, and decrease as the crust cooled.

Although these assumptions are not sufficient to fix the form of δV explicitly, they are sufficient to define two limiting cases. One extreme is the linear increase of δV from zero at time T to some maximum value at $t = 0$. In this case δV has the form

$$\delta V = a\, \overline{V}\, (T - t)$$

The other extreme corresponds to the supposition that the maximum deviation in V was achieved entirely by physical and chemical processes during the actual solidification and that no further separation has occurred since. This corresponds to

$$\delta V = c\, \overline{V} \text{ (a constant)}$$

Figure 2 illustrates these two extreme cases.

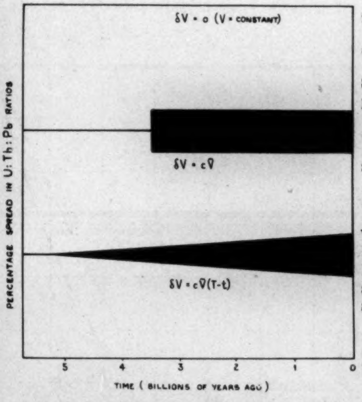
δV = o (V = CONSTANT)
δV = c$\overline{V}$
δV = c$\overline{V}$(T-t)
PERCENTAGE SPREAD IN U:Th:Pb RATIOS
5
4
3
2
1
0
TIME (BILLIONS OF YEARS AGO)

Fig. 2--Schematic representation of spread in uranium, thorium, and lead abundances in the Earth's crust, and the manner in which they may vary with time

Assuming the first extreme case and working out (3) we obtain for Pb^{207}

$$\delta x = (a\overline{V}/\lambda)\,(e^{\lambda T} - e^{\lambda t}) - a\overline{V}\,(T - t)\, e^{\lambda t} \ldots\ldots (5)$$

Similarly it is possible to deduce analogous expressions for the other lead isotopes. For Pb^{206}

$$\delta y = 139\,(a\overline{V}/\lambda')\,(e^{\lambda' T} - e^{\lambda' t}) - 139 a\overline{V}\,(T - t)\, e^{\lambda' t} \ldots (6)$$

and for Pb^{208}

$$\delta z = (b\overline{W}/\lambda'')\,(e^{\lambda'' T} - e^{\lambda'' t}) - b\overline{W}\,(T - t)\, e^{\lambda'' t} \ldots (7)$$

where $\overline{W}$ is the abundance of Th^{232} relative to Pb^{204} in the Earth's crust at the present time, 139 is the present ratio U^{238}/U^{235}, and λ' and λ'' are the decay constants of U^{238} and Th^{232} respectively.

We have taken the values of COLLINS and Others [1953] for the constants: $\overline{V} = 0.0714$, $\overline{W} = 38.2(8)$, $\delta x_{t=0} = 0.35$, $\delta y_{t=0} = 0.75$, and $\delta z_{t=0} = 1.5$, and used for the decay constants $\lambda = 0.980$, $\lambda' = 0.154$, and $\lambda'' = 0.0499$, where the unit of time is 10^9 years.

Inserting these values in (5), (6), and (7), it was found that $T = 5.2 \times 10^9$ years, $a = 0.027 \times 10^{-9}$ years^{-1} and $b = 0.053 \times 10^{-9}$ years^{-1}. Using these values together with (4), it can be shown that for dating by means of the Pb^{206}/Pb^{204} ratio

$$(\delta t)_{206} = (a/\lambda'^2)\,[e^{\lambda'(T-t)} - 1 - \lambda'(T - t)] = 1.15\,[e^{0.154(5.2-t)} - 1 - 0.154\,(5.2 - t)]$$

and for dating by the Pb^{208}/Pb^{204} ratio

$$(\delta t)_{208} = (b/\lambda''^2)\,[e^{\lambda''(T-t)} - 1 - \lambda''\,(T - t)] = 21.3\,[e^{0.0499(5.2-t)} - 1 - 0.0499\,(5.2 - t)]$$

Although a similar formula can be worked out for Pb^{207}, dating by this isotope is unsatisfactory due to the relatively small contribution of radiogenic Pb^{207} during geological time which results in extremely large possible errors.

If the other extreme case is assumed, (that is, $\delta V = c\overline{V}$ and $\delta W = d\overline{W}$), a similar calculation can be made. The resulting expressions for the possible errors in ages are

$$(\delta t)_{206} = 0.596\,[e^{0.154(3.9-t)} - 1]$$

and

$$(\delta t)_{208} = 3.63\,[e^{0.0499(3.9-t)} - 1]$$

Figures 3 and 4 which compare the estimated possible errors calculated for the two extreme cases show that the predicted errors are similar. In calculating the ages for the various common leads the authors have used

$$t_{206} = 6.49 \log_e [1 + (18.45 - v)/9.92] \pm 1.15\,[e^{0.154(5.2-t)} - 1 - 0.154\,(5.2 - t)]$$

$$t_{208} = 20.04 \log_e [1 + (38.40 - z)/38.28] \pm 21.3\,[e^{0.0499(5.2-t)} - 1 - 0.0499\,(5.2 - t)]$$

The formulas for the ages have been obtained by transposing the expressions for the average abundances determined by Collins and Others. The possible error expressions deduced for a linear separation of uranium, thorium, and lead have been used, although it has been pointed out that it does not matter much which of the two extreme formulas are chosen. This method of dating is suitable only for ordinary leads.

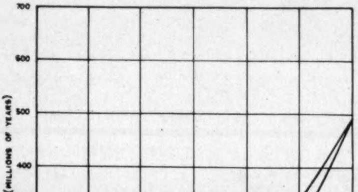

Fig. 3--Possible errors of ages calculated from the Pb^{206}/Pb^{204} ratio

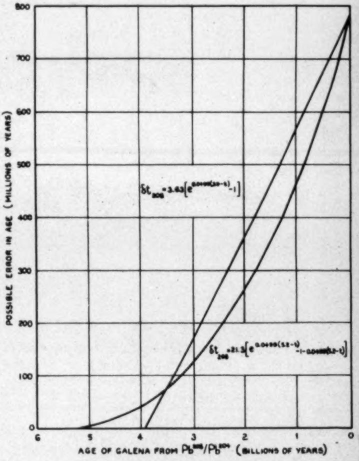

Fig. 4--Possible errors of ages calculated from the Pb^{208}/Pb^{204} ratio

Anomalous leads have very large Pb^{206} and Pb^{208} abundances and hence will give very large negative ages by this method. For instance the anomalous Sudbury leads which will be described in a following section give ages of about -8000 million years. Clearly they cannot be dated in this way. When a large number of anomalous leads of varying isotopic constitution are found in the same deposit, they can be treated in the following manner.

Suppose that the various anomalous leads from one deposit are a series of mixtures of a single ordinary lead and a single radiogenic lead in differing proportions. Represent the measured isotopic abundances Pb^{206}/Pb^{204}, Pb^{207}/Pb^{204}, and Pb^{208}/Pb^{204} by y_m, x_m, and z_m, and the abundances of the corresponding isotopes of the ordinary lead component by y_o, x_o, and z_o. The ratio (radiogenic Pb^{207})/(radiogenic Pb^{206}) should ideally be a constant, R, for all samples from this deposit. R can be determined by least-squares analysis by minimizing the expression

$$\Sigma[(x_m - x_o) - R\,(y_m - y_o)]^2$$

This gives

$$R = [n\,\Sigma(x_m y_m) - \Sigma x_m\,\Sigma y_m]/[n\,\Sigma(y_m^2) - (\Sigma y_m)^2] \quad \ldots\ldots\ldots\ldots\ldots \quad (8)$$

where the summations extend over the n samples.

At any time t the isotopes of uranium are generating lead in the proportion

$$R = \lambda e^{\lambda t}/139\,\lambda' e^{\lambda' t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

Thus if a value of R can be calculated from (8), Eq. (9) gives the time of the radiogenic addition, assuming that the addition took place instantaneously. If the time taken for the radiogenic addition was not negligible, the actual time interval during which the addition took place must bracket the time calculated from (9). Thus the value of t calculated from (8) and (9) represents the earliest time at which the lead could have been separated from the uranium.

In using this method, great care must be taken to insure that a sufficient number of samples are used, and that they show a sufficient variation in isotopic abundance.

Ordinary leads--Isotopic analyses have been made in this laboratory on leads extracted from a number of galena samples in an attempt to determine the ages of deposition of the specimens using the methods outlined previously. The analyses were made using lead tetramethyl as a source of ions in a 180° Nier-type mass spectrometer. The use of lead tetramethyl for isotopic analyses has been described in detail elsewhere by COLLINS and FREEMAN [1951], DIBELER and MOHLER [1951], and COLLINS, RUSSELL, and FARQUHAR [1953].

Table 1 includes the results of the isotopic analyses of eight specimens of galena from ore deposits in several different Precambrian areas. Utilizing the formulas developed in the preceding section for dating leads of the ordinary type, the age values given in Table 2 have been calculated. The mean age quoted for each sample has been obtained by weighting the ages determined from the Pb^{206}/Pb^{204} and Pb^{208}/Pb^{204} ratios inversely as the squares of their respective deviations. The possible error of this mean has been calculated by summing the Pb^{206}/Pb^{204} and Pb^{208}/Pb^{204} possible errors corresponding to the mean age and dividing by $2\sqrt{2}$. It should be noted that the two age values calculated for each sample lie within the deviations obtained on the basis of the divergent hypothesis outlined earlier.

The following information regarding the geological age of the specimens has been kindly supplied by some of the donors of the samples. Sample 1 was associated with the tin mineralization paragenesis cutting the Bushveld Igneous Complex believed to be middle Proterozoic in age. Sample 2 was associated with the Dolomite series of the Transvaal System also cutting the Bushveld Igneous Complex. Sample 3 was obtained from an auriferous vein cutting a greenstone formation of Archean age. The chronological order of these samples is supported by their respective age values listed in Table 2; the values for Samples 1 and 2 indicate that the Dolomite series of the Transvaal System may be considerably older than the tin mineralization. The galena sample from the Rosetta Mine is undoubtedly the oldest yet examined isotopically.

Sample 4 was found in a quartz vein cutting the ancient greenstone schists of the Dharwar Series. The great age calculated for this sample is thus also supported by geological evidence. Sample 5 was obtained from the Mararon Reef, a quartz vein cutting at right angles the fine-grained greenstone lavas which form the country rock. Sample 6 (200 mi from the location of Sample 5) was associated with auriferous quartz stringers injected into the highly folded, dolomitised greenstone tuff bed occurring at the 600-ft level of the Dolomite Lode. The agreement between the two average age values obtained for these two samples indicate that the mineralization in both areas was probably contemporaneous.

Table 1--Isotopic analyses of lead extracted from galena specimens

No.	Location	Value	Relative isotopic abundances			
			Pb^{204}	Pb^{206}	Pb^{207}	Pb^{208}
1	Potgietersrust Dist., Transvaal,	a	1.43(3)[c]	23.30	22.77	52.51
	South Africa[d]	b	1.00	16.26	15.89	35.64
2	Marico Dist., Transvaal,	a	1.49(3)	22.68	23.14	52.68
	South Africa[d]	b	1.00	15.19	15.50	35.28
3	Rosetta Mine, Barberton Dist.,	a	1.64(8)	20.84	23.52	54.02
	Transvaal, South Africa[d]	b	1.00	12.65	14.27	32.78
4	Inguladhal, Chitaldrug Dist.,	a	1.57(0)	22.24	23.14	53.07
	Mysore State, India[e]	b	1.00	14.17	14.74	33.80
5	Phoenix Mine, Norseman,	a	1.54(8)	21.99	23.57	52.92
	Western Australia[f]	b	1.00	14.21	15.23	34.19
6	Copperhead Mine, Bullfinch,	a	1.56(5)	22.20	23.35	52.89
	Western Australia[f]	b	1.00	14.19	14.92	33.80
7	Ivigtut, Greenland[g]	a	1.51(8)	22.54	22.68	53.24
	(Analysis by this laboratory)	b	1.00	14.85	14.94	35.07
8	Ivigtut, Greenland	a	1.54	22.71	22.63	53.12
	(Analysis by NIER [1941])	b	1.00	14.75	14.70	34.5

[a] As percentages. [b] With respect to Pb^{204}. [c] Parenthetic items are the next computed significant figure; the reproducibility of the value is ± 0.05. Donors of samples: [d] L. T. Nel, Geological Survey of South Africa. [e] Ramachandra Rao, Geological Survey of India. [f] D. Campbell, Western Mining Corp., Western Australia. [g] G. G. Suffel, Department of Geology, University of Western Ontario.

Table 2--Age values calculated from isotopic analyses given in Table 1

No.	Age ($\times 10^6$ years)		
	From Pb^{206}/Pb^{204}	From Pb^{208}/Pb^{204}	Mean age value
1	1300 ± 250	900 ± 490	1220 ± 240
2	1840 ± 170	1570 ± 340	1790 ± 170
3	2990 ± 70	2750 ± 150	2950 ± 70
4	2330 ± 120	2270 ± 220	2320 ± 120
5	2310 ± 120	1910 ± 270	2250 ± 120
6	2320 ± 120	2270 ± 220	2300 ± 120
7	2010 ± 150	1670 ± 320	1950 ± 150
8	2060 ± 150	1930 ± 270	2020 ± 140

Sample 7 was associated with cryolite and chalcopyrite. An analysis reported previously by NIER [1941] for a sample of galena from this location is included in Table 1 to provide a rough comparison of the results obtained using different mass spectrometric techniques. The samples analyzed were not identical, so that the observed difference may be partially real. The age value of approximately 2000 million years differs from the late Precambrian age of 600 million years assumed by HOLMES [1946] in his calculation of the time of solidification of the Earth's crust. This discrepancy would be resolved if the deposit could be dated by some other method of age determination.

The Sudbury galenas--Until a year ago galenas from the Tri-State Mines near Joplin, Missouri [NIER, 1938], were the only known anomalous leads in the sense used in this paper. At that time COLLINS, RUSSELL, and FARQUHAR [1953] reported isotopic analyses for two galenas from the Garson and Worthington Mines at the south edge of the Sudbury Basin, which were also anomalous. Since that time the authors have carried out isotopic analyses on a total of 14 galenas from the Sudbury area, the results of which are shown in Table 3. Four of the 14 are ordinary leads and the remainder anomalous.

Table 3--Lead isotopic abundances of Sudbury galenas

No.	Location	Pb^{206}/Pb^{204}	Pb^{207}/Pb^{204}	Pb^{208}/Pb^{204}
1	McKim Mine (1000 ft)	22.89	16.72	44.92
2	McKim Mine (960 ft)	23.03	16.69	45.19
3	McKim Mine (800 ft)	16.30	15.85	36.97
4	McKim Mine (600 ft)	16.43	15.96	36.93
5	Falconbridge Mine (3300 ft)	24.29	17.04	45.70
6	Falconbridge Mine (2400 ft)	23.70	16.92	45.35
7	Falconbridge Mine (1700 ft)	24.20	16.95	45.58
8	Frood Mine (disseminated in wall)	15.99	15.84	36.56
9	Frood Mine (post ore slip)	23.10	16.90	45.04
10	Garson Mine[a]	22.95	16.69	44.79
11	Garson Mine (post ore slip)	23.00	16.61	44.78
12	Worthington Mine	26.00	16.94	52.21
13	Hardy Mine (750 ft)	23.23	16.77	52.64
14	Fairbank Twp. (deformed micropegmatite)	16.20	15.76	36.99

[a] Abundances of Sample 10 have previously been reported incorrectly [COLLINS and others, 1953]; the values given here have been corrected.

Four samples were obtained from the McKim Mine. The two which were found nearer the surface were ordinary leads, while those from greater depths were definitely anomalous. It would be interesting to determine whether this arrangement is merely due to chance, or whether there are distinct regions containing leads of specific isotopic composition. The three samples from the Falconbridge Mine were all anomalous, but all came from fairly great depth. Galena disseminated in the wall rock of the Frood Mine was ordinary, but that found in post-ore slips was anomalous. Galena disseminated in deformed micropegmatites in Fairbank Township toward the interior of the basin was also ordinary. All the galenas reported here with the possible exception of the specimens from Fairbank Township and from the wall rock of the Frood Mine are believed to be later than the main copper-nickel mineralization.

The four samples which the authors believe to be ordinary have been used to estimate the time of deposition of the galena. Calculations carried out as described earlier gave the results shown in Table 4. From a consideration of the various results obtained for the four samples, we believe that the best value for the age of the galenas is 1200 ± 120 million years.

A least-squares analysis was carried out on the 14 samples to determine the best value for the radiogenic Pb^{207}/Pb^{206} ratio. The value obtained was 0.134 ± 0.007, which corresponds to a value of 1300 million years for the maximum possible time since the radiogenic addition took place. Thus the Sudbury galenas are almost certainly younger than 1300 million years, which value agrees very nicely with the estimated age of 1200 million years for the four ordinary samples.

Table 4--Calculated ages of Sudbury ores

No.	Location	Age from Pb^{206}/Pb^{204}	Age from Pb^{208}/Pb^{204}	Weighted mean
		million years	million years	million years
3	McKim Mine	1270 ± 260	730 ± 530	1160 ± 250
4	McKim Mine	1200 ± 270	750 ± 530	1110 ± 250
8	Frood Mine	1430 ± 230	940 ± 480	1340 ± 220
14	Fairbank Twp.	1320 ± 240	730 ± 530	1220 ± 230
Mean of four samples: 1200 ± 120 million years.				

If it can be assumed that the radiogenic additions to the anomalous leads were all produced by some body of radioactive material that contained a fixed uranium to thorium ratio, the relative amount of uranium and thorium can be determined by the amount of radiogenic Pb^{206} and Pb^{208} found in the anomalous ores. The ratio radiogenic Pb^{208}/Pb^{206} was calculated by least squares by the same procedure that has been described in detail for calculating the radiogenic Pb^{207}/Pb^{206} ratio. The radiogenic Pb^{208}/Pb^{206} ratio was found to be 1.54 which would have been generated 1300 million years ago by a radioactive deposit having at the present time a thorium to uranium ratio of 5.2.

The deposits associated with the Sudbury Basin lie in the Keewatin Province of the Canadian Shield which is believed to be 2200 - 2400 million years old. The deposits are apparently associated with a series of large faults which start at the northern border of the Grenville Province and extend northward and westward across the Keewatin Province. The Grenville Province has been dated at 800 - 1100 million years, so that the results obtained from this study of the Sudbury galenas seems to corroborate the theory that the galena was introduced along faults that formed early in the Grenville orogeny.

Calibration sample--Table 5 reports the results of analyses of a calibration sample supplied by R. S. Cannon and L. R. Stieff of the United States Geological Survey. The sample, consisting of spectroscopically pure lead has been analyzed on four separate occasions with the mass spectrometer in this laboratory. The analyses made in this laboratory are given as examples of the reproducibility obtainable using the lead tetramethyl technique.

The results of another laboratory's measurements of this particular sample are in good agreement with those presented below [FARQUHAR and Others, 1953].

Table 5--Isotopic analyses of lead calibration sample

Method	Relative isotopic abundances			
	Pb^{204}	Pb^{206}	Pb^{207}	Pb^{208}
Lead trimethyl$^+$ spectrum A	1.43(8)[a]	23.72	22.60	52.21
Lead trimethyl$^+$ spectrum B	1.45(0)	23.66	22.60	52.31
Lead trimethyl$^+$ spectrum C	1.43(9)	23.74	22.39	52.45
Lead trimethyl$^+$ spectrum D	1.43(2)	23.63	22.57	52.37
Lead$^+$ spectrum D	1.43(5)	23.66	22.56	52.35
Average[b]	1.44(0) ± 0.005	23.70 ± 0.04	22.54 ± 0.06	52.33 ± 0.06

[a] Parenthetic items are the next computed significant figures; the reproducibility of the value is ± 0.05.

[b] Limits of uncertainty are average deviations.

Conclusions--We suggest that the expressions calculated by COLLINS, RUSSELL, and FARQUHAR [1953] for the isotopic abundances of an average lead separated from the crust at a specific time are suitable for dating common lead ores provided that account is taken of the fact that variations in the relative amounts of uranium, thorium, and lead will cause errors in the ages obtained. The expected possible errors have been calculated first by assuming that the maximum percentage deviation in the average uranium/lead and thorium/lead values have been constant during geological time, and second by assuming that the percentage deviations have been growing linearly since the time at which the crust first formed. The expected possible errors for these two extreme cases are similar, both becoming rapidly smaller with increasing age of the sample. The authors believe that useful ages can be obtained for samples older than 1000 million years. In the case of galenas older than 2000 million years the errors are as small as can be obtained by any other known method of geological dating. Twelve samples have been dated in this way.

Anomalous leads have been found at Joplin, Missouri, and in the Sudbury, Ontario, copper-nickel mines. These leads have very high Pb^{206} and Pb^{208} abundances, give large negative ages by the method of dating suggested, and cannot be used in the calculation of Bullard and Stanley to obtain the age of the Earth's crust. A least-squares method is described which gives an upper limit to the age of these samples. These methods have been tried on both anomalous and ordinary leads obtained from the Sudbury Basin area. The results obtained by both methods are consistent with an age of 1200 ± 200 million years. The authors believe that this supports the view that the Sudbury galenas were brought in along faults associated with the Grenville orogeny.

It has often been suggested that common leads can be dated by subtracting from the Pb^{207}/Pb^{204} and the Pb^{206}/Pb^{204} abundances the primeval lead abundances calculated by Holmes and by Bullard and Stanley and thus obtaining a radiogenic Pb^{207}/Pb^{206} ratio. If it can be assumed that the radiogenic contributions are due to an undisturbed association of the lead with uranium prior to the deposition of the lead as a lead mineral, the age of the mineral can be calculated. We believe that this procedure is less satisfactory than the one described here because the former is very sensitive to failures in the basic assumptions and gives no idea of the possible errors which may occur. Ages calculated by this method often bear little relation to the known geological ages.

We stress that the procedures described in this paper are essentially statistical methods. As such, they should be more reliable when suites of samples from a particular location are examined. Although all ages calculated in this paper seem reasonable geologically, the methods cannot be considered proven until a number of checks against other established methods can be obtained.

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THEORY OF COMPLEX NUMBERS IN STRUCTURAL GEOLOGY

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Abstract--A system of plane groups based on the theory of complex numbers is established in a hemisphere of a unit radius and certain relationships are derived for lines located in the same plane and in the planes belonging to different complex number planes. An example for the solution of geological field problems with the use of the theory of complex numbers is given.

Introduction--The application of stereographic and other types of projections, chiefly based on descriptive geometry, is widespread in structural geology. Although the use of those projections usually leads to rapid and relatively accurate graphical solutions, the application of a mathematical method based on the theory of complex numbers may be justified in certain cases when the greater accuracy is desired.

The problem--We can assume, at least during the first steps, that the surface of the Earth is a horizontal plane, and that our Earth block is a hemisphere of radius equal one unit, where the diameter SON is oriented in the true north-south direction and the diameter WOE along an east-west line.

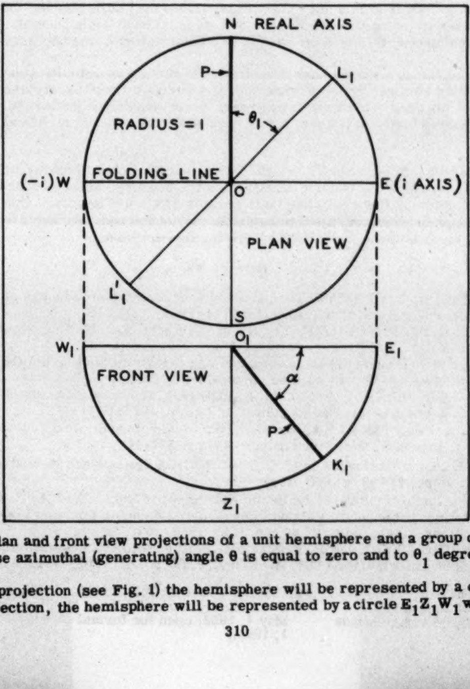

Fig. 1--Plan and front view projections of a unit hemisphere and a group of planes whose azimuthal (generating) angle θ is equal to zero and to θ_1 degrees

In plan view projection (see Fig. 1) the hemisphere will be represented by a circle NESW, and in front view projection, the hemisphere will be represented by a circle $E_1Z_1W_1$ with the line E_1W_1

as a folding line. We can also assume that the circle NESW is a plane of complex number where the line SON is a real axis and the line WOE is an imaginary one. Any line OL_1 drawn from point O, and whose magnitude is equal to one, can be mathematically expressed

$$OL_1 = \boldsymbol{\ell}_1 = \cos\theta_1 + i\sin\theta_1 \quad \ldots\ldots\ldots\ldots \text{(1a)}$$

$$OL_1 = \boldsymbol{\ell}_1 = e^{i\theta} \quad \ldots\ldots\ldots\ldots \text{(1b)}$$

where e = base of Naperian logarithms; θ_1 = angle L_1ON = azimuth of the line OL_1 from a line ON, assumed to be positive in clockwise direction; $i = \sqrt{-1}$ = imaginary number; and $\boldsymbol{\ell}_1$ = vector in plane NESW of unit magnitude. Any straight line, such as SON, $L_1'OL_1$, $L_2'OL_2$, . . . located in the plane of the circle NESW can be considered as a generating line, or the true strike line, of an infinite number of planes whose true dips may vary from 0 to 180°. As an example, a generating line, let us say SON, whose angle of azimuth θ is equal to zero degree, can be considered as the true strike line of an infinite number of planes. Assume that a plane P whose angle of true dip is equal to α degrees, is represented in the northern half of the plan view and in the front view by the lines ON and OK_1 respectively (Fig. 1). Any straight line passing through point O and located in plane P may be mathematically expressed as

$$\left.\begin{aligned} OK_1 &= \boldsymbol{\ell}_1 = \cos\beta_\alpha^{1(0)} + i_\alpha^0 \sin\beta_\alpha^{1(0)} \\ OK_2 &= \boldsymbol{\ell}_2 = \cos\beta_\alpha^{2(0)} + i_\alpha^0 \sin\beta_\alpha^{2(0)} \\ &\ldots\ldots\ldots\ldots\ldots\ldots \\ OK_n &= \boldsymbol{\ell}_n = \cos\beta_\alpha^{n(0)} + i_\alpha^0 \sin\beta_\alpha^{n(0)} \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots \text{(2a)}$$

$$\left.\begin{aligned} OK_1 &= \boldsymbol{\ell}_1 = e^{i_\alpha^0 \beta_\alpha^{1(0)}} \\ OK_2 &= \boldsymbol{\ell}_2 = e^{i_\alpha^0 \beta_\alpha^{2(0)}} \\ &\ldots\ldots\ldots\ldots \\ OK_n &= \boldsymbol{\ell}_n = e^{i_\alpha^0 \beta_\alpha^{n(0)}} \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots \text{(2b)}$$

where ON = real axis; OK = imaginary axis located in the direction of true dip; β = angle in the plane NOK_1 between any line in the plane and passing through point O, and the line ON, positive in clockwise direction; $\beta_\alpha^{1(0)}, \beta_\alpha^{2(0)}$ = angles in the plane NOK whose true dip is equal to α degrees; α = angle of true dip; i_α^0 = imaginary axis lying in plane ONK_1 dipping east α degrees and whose azimuthal angle θ is equal to zero degree; and $\boldsymbol{\ell}_1, \boldsymbol{\ell}_2, \ldots, \boldsymbol{\ell}_n$ = line vectors of unit magnitude.

For any plane P_1 whose azimuthal angle is equal to θ degrees, unit vectors lying in the plane and passing through point O are given by

$$\left.\begin{aligned} OK_1 &= \boldsymbol{\ell}_1 = \cos\beta_\alpha^{1(\theta)} + i_\alpha^\theta \sin\beta_\alpha^{1(\theta)} = e^{i_\alpha^\theta \beta_\alpha^{1(\theta)}} \\ OK_2 &= \boldsymbol{\ell}_2 = \cos\beta_\alpha^{2(\theta)} + i_\alpha^\theta \sin\beta_\alpha^{2(\theta)} = e^{i_\alpha^\theta \beta_\alpha^{2(\theta)}} \\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ OK_n &= \boldsymbol{\ell}_n = \cos\beta_\alpha^{n(\theta)} + i_\alpha^\theta \sin\beta_\alpha^{n(\theta)} = e^{i_\alpha^\theta \beta_\alpha^{n(\theta)}} \end{aligned}\right\} \quad \ldots\ldots\ldots \text{(3)}$$

where α = angle of true dip of plane P_1; i_α^θ = imaginary axis located in the direction of true dip; real axis = the line of intersection of plane P_1 with the horizontal plane; β_α^θ = angle between the real axis and any straight line passing through O and lying in the plane; θ = azimuthal angle of the true strike line from ON line.

Angular relationships in a plane whose azimuthal angle θ is equal to zero--According to a well-known formula

$$\tan\psi = \tan\alpha \sin\phi \quad \ldots\ldots\ldots\ldots \text{(4)}$$

where ψ = angle of apparent dip; α = angle of true dip; and ϕ = angle between the line ON, the direction of true strike, and the direction of apparent dip, measured in a horizontal plane.

Eq. (4) can be expressed as

$$\tan\psi = \tan\alpha \sin\theta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

where the angle ϕ is equal to the angle θ, the azimuthal angle of a vertical plane passing through the direction of apparent dip. Any line on this vertical plane can be expressed as

$$\ell_n = \cos\beta_{90^\circ}^{n(\theta)} + i_{90^\circ}^{\theta} \sin\beta_{90^\circ}^{n(\theta)} = e^{i_{90}^{\theta}\beta_{90}^{n(\theta)}} \quad \ldots\ldots\ldots\ldots\ldots \quad (6)$$

where $\alpha = 90^\circ$ = angle of the true dip, and n = any line in the vertical plane.

For a plane whose true dip is equal to α degrees and true strike is located along the line ON, that is the angle θ is equal to zero, the following formulas are valid

$$\left.\begin{array}{l} \ell_1 = \cos\beta_{\alpha}^{1(0)} + i_{\alpha}^{0} \sin\beta_{\alpha}^{1(0)} = e^{i_{\alpha}^{0}\beta_{\alpha}^{1(0)}} \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ \ell_n = \cos\beta_{\alpha}^{n(0)} + i_{\alpha}^{0} \sin\beta_{\alpha}^{n(0)} = e^{i_{\alpha}^{0}\beta_{\alpha}^{n(0)}} \end{array}\right\} \quad \ldots\ldots\ldots\ldots\ldots \quad (7)$$

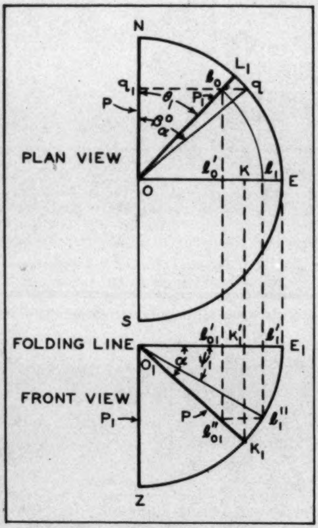

Fig. 2--Plan and front view projections of eastern half of a unit hemisphere and of planes P and P_1 whose azimuthal (generating) lines are zero and θ_1 degrees; P_1 is a vertical plane

Assume the eastern half of a hemisphere (Fig. 2) with plane P passing through line SON and dipping α degrees east. The lines ON and OK_1 are the plan view and front view projections of the true strike and true dip lines, respectively. Assume also a vertical plane P_1 passing through point O and intersecting the plane P along a line whose plan and front view projections are the lines $O\ell_0$ and $O\ell_{01}''$, respectively. The azimuth of the plane P_1 measured in the horizontal plane, that is the angle NOL_1, is equal to θ_1 degrees. This line of intersection, according to (6) and (7), can be expressed as

$$\ell_1 = \cos\beta_{90}^{1(\theta_1)} + i_{90}^{\theta_1} \sin\beta_{90}^{1} = e^{i_{90}^{\theta_1}\beta_{90}^{1(\theta)}} \quad \ldots\ldots \quad (8a)$$

$$\ell_{11} = \cos\beta_{\alpha}^{1(0)} + i_{\alpha} \sin\beta_{\alpha}^{1(0)} = e^{i_{\alpha}^{0}\beta_{\alpha}^{1(0)}} \quad \ldots\ldots \quad (8b)$$

where $\beta_{90}^{1(\theta)}$ = angle in the vertical plane P_1 between the line OL_1 and the line of intersection of P and P_1 planes; $\beta_{\alpha}^{1(0)}$ = angle in α plane P between the line ON and the line of intersection; θ_1 = azimuthal angle of the line OL_1 in the horizontal plane NES; $i_{90}^{\theta_1}$ = imaginary axis OZ lying in the plane P_1; and i_{α}^{0} = imaginary axis OK_1 (front view projection).

Relationship among $\theta, \beta_{\alpha}^{0}$, and β_{90}^{θ}--For the vertical planes $P_1, P_2, \ldots, P_n$, intersecting plane P whose true dip is equal to α degrees, the angles of apparent dips $\psi_1, \psi_2, \ldots, \psi_n$ are respectively identical with the angles $\beta_{90}^{1(\theta_1)}, \beta_{90}^{2(\theta_2)}, \ldots, \beta_{90}^{n(\theta_n)}$ where the angles β_{90}^{θ} are the angles lying in the planes $P_1, P_2, \ldots, P_n$ and are measured from the azimuthal, or generating, line to the lines of intersection of their respective vertical plane with plane P. Therefore, (5) can be given as

$$\tan \psi_1 = \tan \beta_{90}^{1(\theta_1)} = \tan \alpha \sin \theta_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(9a)}$$

$$\tan \psi_2 = \tan \beta_{90}^{2(\theta_2)} = \tan \alpha \sin \theta_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(9b)}$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

$$\tan \psi_n = \tan \beta_{90}^{n(\theta_n)} = \tan \alpha \sin \theta_n \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(9c)}$$

where $\theta_1, \theta_2, \ldots, \theta_n$ are the azimuthal angles, that is, the azimuths of the generating lines from line ON.

By rotating plane P about the horizontal axis ON until the plane coincides with the horizontal semicircle NES, point ℓ_0, a plan view projection of a piercing point of the intersection line of P and P_1 planes will move perpendicularly to line ON until its intersection with the circle at point q. In triangle $qq_1{}^0$ the angle NOq is equal to β_α^0 degrees (see Fig. 2).

From triangle q_1Oq we have

$$Oq_1 = Oq \cos \beta_\alpha^{1(0)} = \cos \beta_\alpha^{1(0)} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(10)}$$

because $Oq = 1$.

From triangle $q_1O\ell_0$ we have

$$Oq_1 = O\ell_0 \cos \theta_1 = O\ell' \cos \theta_1 = O\ell_1' \cos \theta_1 = \cos \psi_1 \cos \theta_1 \quad \ldots\ldots\ldots \text{(11)}$$

because from triangle $O_1\ell_1'\ell_1''$, $O_1\ell_1' = O_1\ell_1'' \cos \psi_1 = \cos \psi_1$.

By substituting the magnitude of Oq_1 from (11) into (10) we obtain a set of equations

$$\cos \beta_\alpha^{1(0)} = \cos \psi_1 \cos \theta_1 = \cos \beta_{90}^{1(\theta_1)} \cos \theta_1 \quad \ldots\ldots\ldots\ldots\ldots \text{(12a)}$$

$$\cos \beta_\alpha^{2(0)} = \cos \psi_2 \cos \theta_2 = \cos \beta_{90}^{2(\theta_2)} \cos \theta_2 \quad \ldots\ldots\ldots\ldots\ldots \text{(12b)}$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

$$\cos \beta_\alpha^{n(0)} = \cos \psi_n \cos \theta_n = \cos \beta_{90}^{n(\theta_n)} \cos \theta_n \quad \ldots\ldots\ldots\ldots\ldots \text{(12c)}$$

because $\psi_1, \psi_2, \ldots, \psi_n$ are respectively identical with the angles $\beta_{90}^{1(\theta_1)}, \beta_{90}^{2(\theta_2)}, \ldots, \beta_{90}^{n(\theta_n)}$ located in their respective vertical plane with the azimuthal angles equal to $\theta_1, \theta_2, \ldots, \theta_n$ degrees.

By combining (9a) and (12a) we obtain

$$\tan \psi_1 = \tan \beta_{90}^{1(\theta_1)} = \tan \alpha \sin \theta_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(13a)}$$

$$\cos \beta_\alpha^{1(0)} = \cos \beta_{90}^{1(\theta_1)} \cos \theta_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(13b)}$$

By dividing (13a) by (13b)

$$\tan \beta_{90}^{1(\theta_1)} / \cos \beta_\alpha^{1(0)} = \tan \alpha \sin \theta_1 / \cos \beta_{90}^{1(\theta_1)} \cos \theta_1 \quad \ldots\ldots\ldots\ldots \text{(14)}$$

From (14) we obtain

$$\sin \beta_{90}^{1(\theta_1)} / \cos \beta_\alpha^{1(0)} = \tan \alpha \tan \theta_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(15)}$$

Relationship between β angles of a group of planes whose generating (azimuthal) line has an azimuth θ equal to zero degree--According to (7), the straight lines passing through point O and lying in the planes whose true dips are α_1 and α_2 degrees respectively, can be expressed as

$$\left.\begin{array}{l} \ell_1 = \cos\beta^{1(0)}_{\alpha_1} + i^0_{\alpha_1}\sin\beta^{1(0)}_{\alpha_1} = e^{i^0_{\alpha_1}\beta^{1(0)}_{\alpha_1}} \\ \ell_2 = \cos\beta^{2(0)}_{\alpha_1} + i^0_{\alpha_1}\sin\beta^{2(0)}_{\alpha_1} = e^{i^0_{\alpha_1}\beta^{2(0)}_{\alpha_1}} \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ \ell_n = \cos\beta^{n(0)}_{\alpha_1} + i^0_{\alpha_1}\sin\beta^{n(0)}_{\alpha_1} = e^{i^0_{\alpha_1}\beta^{n(0)}_{\alpha_1}} \end{array}\right\} \quad \ldots\ldots\ldots\ldots (16a)$$

and

$$\left.\begin{array}{l} \ell_{12} = \cos\beta^{1(0)}_{\alpha_2} + i^0_{\alpha_2}\sin\beta^{1(0)}_{\alpha_2} = e^{i^0_{\alpha_2}\beta^{1(0)}_{\alpha_2}} \\ \ell_{22} = \cos\beta^{2(0)}_{\alpha_2} + i^0_{\alpha_2}\sin\beta^{2(0)}_{\alpha_2} = e^{i^0_{\alpha_2}\beta^{2(0)}_{\alpha_2}} \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ \ell_{n2} = \cos\beta^{n(0)}_{\alpha_2} + i^0_{\alpha_2}\sin\beta^{n(0)}_{\alpha_2} = e^{i^0_{\alpha_2}\beta^{n(0)}_{\alpha_2}} \end{array}\right\} \quad \ldots\ldots\ldots\ldots (16b)$$

Auxiliary coordinate Z--In order to expedite the solution of a problem, it might be necessary, in certain cases, to use an additional coordinate Z, the depth of the end of a vector line in any plane from a horizontal plane NESW. From triangles $O_1K_1K_1'$ (Fig. 1 and 2) and triangle $O_1\ell_1'\ell_1''$ (Fig. 2), we have

$$K_1K_1' = Z^{K_1(0)}_{\alpha} = O_1K_1 \sin\alpha = \sin\alpha \ldots\ldots\ldots\ldots\ldots\ldots (17a)$$

$$\ell_1'\ell_1'' = Z^{\ell''(\theta_1)}_{90} = O_1\ell_1''\sin\psi_1 = \sin\psi_1 = \sin\beta^{1(\theta_1)}_{90} \quad \ldots\ldots\ldots\ldots (17b)$$

because $O_1K_1 = O_1\ell_1'' = 1$; and in general for any line in a plane

$$Z^{x(0)}_{\alpha} = \sin\beta^{x(0)}_{\alpha}$$

where $Z^{K_1(0)}_{\alpha}$ = depth of point K_1 located in a plane dipping α degrees east with an azimuthal angle equal to zero degrees; $Z^{\ell_1''(\theta_1)}_{90}$ = depth of point ℓ_1'' located in a vertical plane P_1, whose azimuthal angle of the generating line OL is equal to θ_1 degrees; β^1_{90} = angle in the vertical P_1 plane; and $\beta^{x_1(0)}_{\alpha}$ = angle in a plane dipping α degrees, whose azimuthal angle is zero degree.

Angular relationships in a plane whose azimuthal angle is not equal to zero--Assume plane P_1 whose azimuthal angle, that is the angle of generating line, is θ_1 degrees, and whose angle of true dip is α_1 degrees SE. On plan and front view projections plane P_1 will be indicated by a true strike line, that is the generating line OL_1, and by direction of the true dip Ot. Point t′ is a plan view projection of a point where a unit vector line located both in plane P_1 and vertical plane passing through the true dip direction will pierce the unit hemisphere (Fig. 3). By rotating line Ot in plan view until its intersection with line OE at t″, we obtain the angle $E_1O_1t_1'$ equal to α_1 degrees where t_1' is a projection of t″ on a circle E_1ZW_1.

Assume line OL and the direction of line Ot located in plane P_1 are the real and imaginary axes, respectively. The unit vector passing through point O and lying in plane P_1 will be

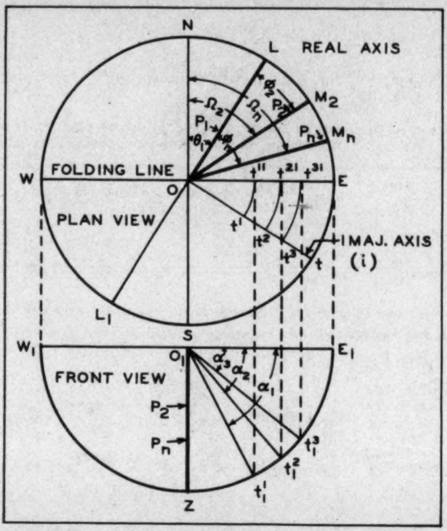
N
L
REAL AXIS
Ω_2
Ω_n
ϕ_2
P_2
M_2
P_1
θ_1
ϕ_n
P_n
M_n
FOLDING LINE
W
O
E
t¹'
t²'
t³'
PLAN VIEW
t'
t²
t³
t
IMAJ. AXIS
(i)
L_1
S
W_1
O_1
E_1
α_3
α_2
α_1
FRONT VIEW
P_2
P_n
t_1^3
t_1^2
t_1^1
Z

Fig. 3--Plan and front view projections of a unit hemisphere and a group of planes whose azimuthal (generating) angle is equal to θ_1 degrees and the true dips are $\alpha_1, \alpha_2, \alpha_3, \ldots$, respectively

$$\left.\begin{array}{l}
\ell_1 = \cos\beta_\alpha^{1(\theta_1)} + i_\alpha^{\theta_1}\sin\beta_\alpha^{1(\theta_1)} = e^{i_\alpha^{\theta_1}\beta_\alpha^{1(\theta_1)}} \\
\ell_2 = \cos\beta_\alpha^{2(\theta_1)} + i_\alpha^{\theta_1}\sin\beta_\alpha^{2(\theta_1)} = e^{i_\alpha^{\theta_1}\beta_\alpha^{2(\theta_1)}} \\
\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\
\ell_n = \cos\beta_\alpha^{n(\theta_1)} + i_\alpha^{\theta_1}\sin\beta_\alpha^{n(\theta_1)} = e^{i_\alpha^{\theta_1}\beta_\alpha^{n(\theta_1)}}
\end{array}\right\} \ldots\ldots\ldots\ldots (18)$$

where $\beta_\alpha^{1(\theta_1)}, \beta_\alpha^{2(\theta_2)}$ = azimuths of vector lines in plane P_1 from line OL, positive clockwise; and $i_\alpha^{\theta_1}$ = imaginary axis in plane P_1.

For a group of planes dipping $\alpha_1, \alpha_2, \ldots, \alpha_n$ degrees and with the same generating line whose azimuthal angle is equal to θ_1 degrees, we have

$$\ell_1 = \cos\beta_{\alpha_1}^{1(\theta_1)} + i_{\alpha_1}^{\theta_1}\sin\beta_{\alpha_1}^{1(\theta_1)} = e^{i_{\alpha_1}^{\theta_1}\beta_{\alpha_1}^{1(\theta_1)}} \ldots\ldots\ldots\ldots (19a)$$

$$\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots$$

$$\ell_n = \cos\beta_{\alpha_1}^{n(\theta_1)} + i_{\alpha_1}^{\theta_1}\sin\beta_{\alpha_1}^{n(\theta_1)} = e^{i_{\alpha_1}^{\theta_1}\beta_{\alpha_1}^{n(\theta_1)}} \ldots\ldots\ldots\ldots (19b)$$

and from (19)

$$\cos^2 \beta_{\alpha_1}^{1(\theta_1)} + \sin^2 \beta_{\alpha_1}^{1(\theta_1)} = \cos^2 \beta_{\alpha_1}^{2(\theta_1)} + \sin^2 \beta_{\alpha_1}^{2(\theta_1)} = \ldots = \ldots = \cos^2 \beta_{\alpha_2}^{12(\theta_1)}$$

$$+ \sin^2 \beta_{\alpha_2}^{1n(\theta_1)} = \ldots = \cos^2 \beta_{\alpha_n}^{1n(\theta_1)} + \sin^2 \beta_{\alpha_n}^{1n(\theta_1)} = \ldots = 1 \quad \ldots\ldots\ldots\ldots \quad (20)$$

By passing any vertical plane, let us say, P_2 (Fig. 3), whose plan and front view projections are the lines OM_2 and O_1Z respectively, the following relationship derived from (9) can be set

$$\tan \beta_{90}^{1(\phi_2)} = \tan \beta_{90}^{1(\Omega_2 - \theta_1)} = \tan \alpha \sin \phi_2 = \tan \alpha \sin (\Omega_2 - \theta_1) \quad \ldots\ldots\ldots\ldots \quad (21a)$$

and for a vertical plane P_n

$$\tan \beta_{90}^{1(\phi_n)} = \tan \beta_{90}^{1(\Omega_n - \theta_1)} = \tan \alpha \sin \phi_n = \tan \alpha \sin (\Omega_n - \theta_1) \quad \ldots\ldots\ldots\ldots \quad (21b)$$

where $\beta_{90}^{\phi_2}$ = angle in plane P_2 counting clockwise from line OM_2; α = angle of true dip of plane P_1; Ω_2 = angle between the line ON and the true strike of plane P_2; and ϕ_2 = angle between the true strikes of planes P_1 and P_2.

From (12) we have

$$\left.\begin{array}{l}
\cos \beta_{\alpha}^{1(\theta_1)} = \cos \beta_{90}^{1(\phi_2)} \times \cos \phi_2 = \cos \beta_{90}^{1(\Omega_2 - \theta_1)} \times \cos \phi_2 \\
\cos \beta_{\alpha}^{2(\theta_1)} = \cos \beta_{90}^{2(\phi_3)} \times \cos \phi_3 = \cos \beta_{90}^{2(\Omega_3 - \theta_1)} \times \cos \phi_3 \\
\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\
\cos \beta_{\alpha}^{n(\theta_1)} = \cos \beta_{90}^{n(\phi_{n+1})} \times \cos \phi_{n+1} = \cos \beta_{90}^{n(\Omega_{n+1} - \theta_1)} \times \cos \phi_{n+1}
\end{array}\right\} \ldots\ldots \quad (22)$$

and from (15)

$$\left.\begin{array}{l}
\sin \beta_{90}^{1(\phi_2)} / \cos \beta_{\alpha}^{1(\theta_1)} = \tan \alpha \tan \phi_2 \\
\sin \beta_{90}^{2(\phi_3)} / \cos \beta_{\alpha}^{2(\theta_1)} = \tan \alpha \tan \phi_3 \\
\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\
\sin \beta_{90}^{n(\phi_{n+1})} / \cos \beta_{\alpha}^{n(\theta_n)} = \tan \alpha \tan \phi_{n+1}
\end{array}\right\} \ldots\ldots\ldots\ldots\ldots \quad (23)$$

where $\beta_{\alpha}^{\theta_1}$ = angles in plane P_1; $\beta_{90}^{\theta_2}$ = angles in a vertical plane P_2; $\beta_{90}^{\theta_n}$ = angles in a vertical plane P_n; α = angle of the true dip of plane P_1; $\phi_2 = \Omega_2 - \theta_1$; . . .; $\phi_n = \Omega_n - \theta_1$; and θ_1 = azimuthal angle of the plane whose generating line is the line OL of plane P_1.

Example--Find the angle of true dip α and the angle of true strike θ of a formation whose apparent dips along the N20°E and N50°E lines are 16°06′ and 26°34′ respectively. Solution: Let us draw lines OM_1 and OM_2 on a plan view projection of a hemisphere (Fig. 4). According to the conditions of the problem the azimuths from ON of the lines OM_1 and OM_2 are N20°E and N50°E respectively. The direction of the true strike of the formation under consideration may be either in a position I or II. By designating as follows

Ω_1 = angle NOM_1 = azimuth of line OM_1 = 20°

Ω_2 = angle NOM_2 = azimuth of line OM_2 = 50°

ϕ_1 = angle IOM_1; ϕ_2 = angle IOM_2

ϕ_1^1 = angle $IIOM_2$; ϕ_2^2 = angle $IIOM_2$

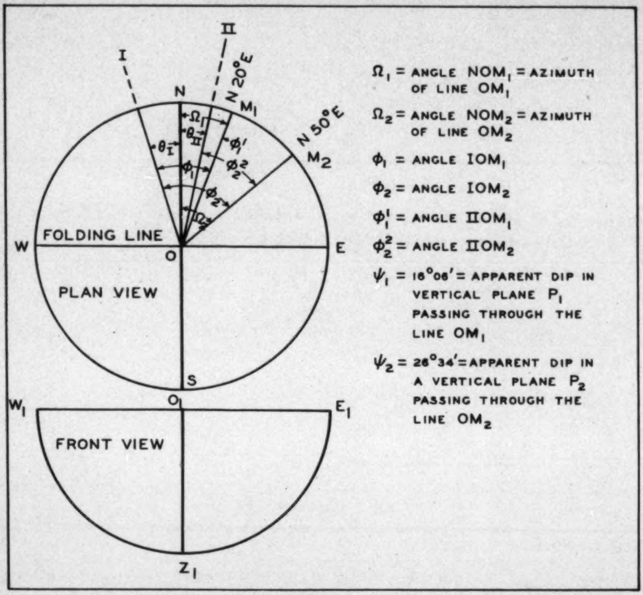
I
II
N 20°E
N
M1
N 50°E
M2
Ω1
θII
θI
φ1'
φ2²
φ1
φ2
Ω2
FOLDING LINE
W
O
E
PLAN VIEW
S
W1
O1
E1
FRONT VIEW
Z1
Ω1 = ANGLE NOM1 = AZIMUTH OF LINE OM1
Ω2 = ANGLE NOM2 = AZIMUTH OF LINE OM2
φ1 = ANGLE IOM1
φ2 = ANGLE IOM2
φ1¹ = ANGLE IIOM1
φ2² = ANGLE IIOM2
ψ1 = 16°06' = APPARENT DIP IN VERTICAL PLANE P1 PASSING THROUGH THE LINE OM1
ψ2 = 26°34' = APPARENT DIP IN A VERTICAL PLANE P2 PASSING THROUGH THE LINE OM2

Fig. 4--Plan and front view projections of a unit hemisphere for the solution of example

ψ_1 = apparent dip in a vertical plane passing through the line OM_1 = 16°06′
ψ_2 = apparent dip in a vertical plane passing through the line OM_2 = 26°34′
θ_I, θ_{II} = azimuths of generating lines of the formation under consideration

For position I the following equations can be set

$$\phi_1 - \theta_I = \Omega_1 \quad \text{(24a)}$$

$$\phi_2 - \theta_I = \Omega_2 \quad \text{(24b)}$$

For position II the following equations can be set

$$\phi_1^1 + \theta_{II} = \Omega_1 \quad \text{(25a)}$$

$$\phi_2^2 + \theta_{II} = \Omega_2 \quad \text{(25b)}$$

or from (24) and (25)

$$\phi_1 = \Omega_1 + \theta_I \quad \text{(26a)}$$

$$\phi_2 = \Omega_2 + \theta_I \quad \text{(26b)}$$

$$\phi_1^1 = \Omega_1 - \theta_{II} \quad \text{(26c)}$$

$$\phi_2^2 = \Omega_2 - \theta_{II} \quad \text{(26d)}$$

From (21) and (26) we obtain

$$\tan \beta_{90}^{\phi_1} = \tan \beta_{90}^{(\Omega_1 + \theta_I)} = \tan \alpha \sin \phi_1 \tag{27a}$$

$$\tan \beta_{90}^{\phi_2} = \tan \beta_{90}^{(\Omega_2 + \theta_I)} = \tan \alpha \sin \phi_2 \tag{27b}$$

$$\tan \beta_{90}^{\phi_1^1} = \tan \beta_{90}^{(\Omega_1 - \theta_{II})} = \tan \alpha \sin \phi_1^1 \tag{27c}$$

$$\tan \beta_{90}^{\phi_2^2} = \tan \beta_{90}^{(\Omega_2 - \theta_{II})} = \tan \alpha \sin \phi_2^2 \tag{27d}$$

but the angles $\beta_{90}^{\phi_1}, \beta_{90}^{\phi_2}, \ldots$, are located in their corresponding vertical planes passing through the lines OM_1 and OM_2 and are equal to the corresponding apparent dips. Therefore

$$\beta_{90}^{\phi_1} = \beta_{90}^{\phi_1^1} = \psi_1 \tag{28a}$$

$$\beta_{90}^{\phi_2} = \beta_{90}^{\phi_2^2} = \psi_2 \tag{28b}$$

By substituting (28) into (27) we obtain

$$\tan \psi_1 = \tan \alpha \sin \phi_1 \tag{29a}$$

$$\tan \psi_2 = \tan \alpha \sin \phi_2 \tag{29b}$$

$$\tan \psi_1 = \tan \alpha \sin \phi_1^1 \tag{29c}$$

$$\tan \psi_2 = \tan \alpha \sin \phi_2^2 \tag{29d}$$

From (29) we have

$$(a)/(b) = \tan \psi_1 / \tan \psi_2 = \sin \phi_1 / \sin \phi_2 \tag{30a}$$

$$(c)/(d) = \tan \psi_1 / \tan \psi_2 = \sin \phi_1^1 / \sin \phi_2^2 \tag{30b}$$

Also from Figure 4 and the condition of the problem we have

$$\tan \psi_1 = \tan 16^\circ 06' = 0.2886 \tag{31a}$$

$$\tan \psi_2 = \tan 26^\circ 34' = 0.5000 \tag{31b}$$

$$\phi_2 - \phi_1 = \phi_2^1 - \phi_2^2 = 50^\circ - 20^\circ = 30^\circ \tag{31c}$$

By substituting (31) into (30) we have

$$0.2886/0.5000 = 0.5772 = \sin \phi_1 / \sin (30 + \phi_1) \tag{32a}$$

$$0.2886/0.5000 = 0.5772 = \sin \phi_1^1 / \sin (30 + \phi_1^1) \tag{32b}$$

or from (32)

$$0.5772 = \sin \phi_1 / (\sin 30 \cos \phi_1 + \cos 30 \sin \phi_1) \tag{33a}$$

$$0.5772 = \sin \phi_1^1 / (\sin 30 \cos \phi_1^1 + \cos 30 \sin \phi_1^1) \tag{33b}$$

From (33)

$$0.5772 = \sin \phi_1 / (0.5 \cos \phi_1 + 0.8660 \sin \phi_1) \tag{34a}$$

$$0.5772 = \sin \phi_1^1 / (0.5 \cos \phi_1^1 + 0.8660 \sin \phi_1^1) \tag{34b}$$

or from (34)

$$0.5772\,(0.5 \cos \phi_1 + 0.8660 \sin \phi_1) = 0.2886 \cos \phi_1 + 0.4999 \sin \phi_1 = \sin \phi_1 \quad \ldots\ldots (35a)$$

$$0.5772\,(0.5 \cos \phi_1^1 + 0.8660 \sin \phi_1^1) = 0.2886 \cos \phi_1^1 + 0.4999 \sin \phi_1^1 = \sin \phi_1^1 \quad \ldots\ldots (35b)$$

By designating $\sin \phi_1 = x$, and $\cos \phi_1 = \sqrt{1 - x^2}$ and transposing we have from (35)

$$0.2886 \sqrt{1 - x^2} = x - 0.4999X = 0.5001X \quad \ldots\ldots (36)$$

or

$$0.0833\,(1 - x^2) = 0.2501X^2 \quad \ldots\ldots (37)$$

From (37) we obtain

$$x = 0.500 = \sin \psi_1 = \sin 30^\circ \quad \ldots\ldots (38)$$

By substituting the value of ψ_1 into (24a) we have

$$30^\circ - \theta_I = 20^\circ \quad \ldots\ldots (39)$$

or

$$\theta_I = 30^\circ - 20^\circ = 10^\circ \quad \ldots\ldots (40)$$

From (24b) we have

$$\phi_2 = \Omega_2 + \theta_1 = 50^\circ + 10^\circ = 60^\circ \quad \ldots\ldots (41)$$

By substituting the values of ϕ_1 and ψ_1 into (29a), the true dip is found as follows

$$\tan \psi_1 = \tan 16^\circ 06' = 0.2886 = \tan \alpha \sin \phi_1 = \tan \alpha\, 0.4999 \quad \ldots\ldots (42)$$

or from (42)

$$0.2886/0.4999 = 0.773 = \tan \alpha = \tan 30^\circ \quad \ldots\ldots (43)$$

or the true dip = 30°.

Therefore the true strike and dip lines of the formation under consideration will be given respectively by

$$\cos \theta_1 + i \sin \theta_1 = \cos(-10^\circ) + i^{\theta_1}_{30^\circ} \sin(-10^\circ) = \cos 10^\circ - i^{\theta_1}_{30^\circ} \sin 10^\circ \quad \ldots\ldots (44a)$$

$$\cos \beta^{\theta_1}_{\alpha} + i^{\theta_1}_{\alpha} \sin \beta^{\theta_1}_{\alpha} = \cos 90^{\theta_1}_{\alpha} + i^{\theta_1}_{\alpha} \sin 90^{\theta_1}_{\alpha} = e^{\left(i^{-10^\circ}_{30^\circ}\ 90^{\circ\,-10^\circ}_{\ 30^\circ}\right)} \quad \ldots\ldots (44b)$$

where e = base of Naperian logarithms.

Summary and conclusions--A system of plane groups based on the theory of complex numbers is established in a unit hemisphere and a certain relationship is established for strike and dip lines located in various group planes.

It is probable that for certain types of problems related to mining geology, a complex number system established in an infinite space should be used.

Acknowledgment--I express my thanks to A. C. Spreng of the Geology Department and Bernard Cohen of the Physics Department for their helpful suggestions; also to L. C. Christianson for execution of the drawings, and to Mrs. H. M. Groves for checking and typing the manuscript, all of them with the Missouri School of Mines and Metallurgy, University of Missouri.

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REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

FISCHBACH, JOSEPH W., Solution of Least-Squares Problems by an N-Step Gradient Method, Ballistic Research Lab., Aberdeen Proving Ground, Md., Tech. Note 719, 7 pp., 1952.

One of the recent methods added to a host of techniques for solving a system of linear equations is the gradient method. The author considers a system of linear algebraic equations of the form $Ax + b = 0$, where A is a matrix of dimensions (M, N), x the unknown vector and b the vector of absolute terms. The vector x is found by minimizing the quadratic form

$$J(x) = (Ax + b, Ax + b)$$

making use of Stiefel's principle of the relaxation method. The procedure with slight modification is readily adapted to the case of normal equations in which case A is positive definite.

The iterative method used by the author to solve $Ax + b = 0$ finds the vector x without having to determine first the normal equations explicitly and does it in exactly N cycles. The number of multiplications in such a procedure while it may be in the ratio of 10 to 1 with respect to a standard method such as the Gauss-Doolittle elimination, has the advantage of being well adapted to high speed computing machines and consequently the absence of a convergence accelerating process is not too serious a disadvantage.

Unlike many iterative methods which start with some preliminary approximation to the solution, determine for each equation the "residual" and change the preliminary values successively so as to reduce these residuals, the N-step gradient method is independent of the initial iterating vector and consequently the null vector may be used for the zero cycle.

The reviewer believes that the extension of the N-step gradient method to the numerical solution of ordinary differential equations will be a very valuable contribution to the field of numerical analysis. Several methods for the solution of ordinary differential equations have come to prominence in recent years. One is the Monte Carlo method in which a system of differential equations is replaced by a system of finite difference equations. These are solved by interpreting them as describing a random process and simulating the random process by generating random numbers in the machine. It appears at present that a gradient method would be far preferable and better adapted to high speed machines.

JOSEPH L. STEARN

NEWELL, NORMAN D., J. KEITH RIGBY, ALFRED G. FISCHER, A. J. WHITEMAN, JOHN E. HICKOX, and JOHN S. BRADLEY, The Permian Reef Complex of the Guadalupe Mountains Region, Texas and New Mexico: A Study in Paleoecology, W. H. Freeman and Co., San Francisco, xix + 236 pp., with 32 plates in a separate section, and 85 text figures, 1953, $7.50.

This book is a masterful and exhaustive treatment of an area that combines examples of two types of structures that are important in petroleum geology, basins and large assemblages of reefs.

From the subtitle of the work, A Study in Paleoecology, one might expect a considerable part of the book to be devoted to this subject. At first glance, therefore, it might seem that a single chapter of 23 pages on paleoecology out of a total of 209 text-pages would be inadequate. Actually, however, the data supplied in the other five chapters, Geologic Setting of the Reefs, Stratigraphy, Reef Complex and Associated Sedimentary Phases, Paleontology, and Diagenesis are essential to the intensive treatment of the Paleoecology of the Permian Rocks of Chapter Seven.

A great value of the book lies in the fact that much of the information given and many of the concepts developed can be applied to similar situations in other areas. For example, the double basin in northern Texas and southern Oklahoma is the same age as the one in western Texas and is closely analogous to it in many respects, although reefs are less abundant and prominent. There are extensive reefs in the Devonian of the western Canada Basin, study of which will no doubt be aided by the volume under review, and even less similar situations such as the Tertiary reefs of the Kirkuk Field in the Middle East can no doubt be studied more effectively in the light of the ideas there presented.

Some controversial subjects are perhaps treated a little too positively. For example, agreement is by no means general that turbidity currents play as important a role in emplacing sediments as is assigned to them here.

It is unfortunate that many authors and publishers seem to consider that the important work is done when the text of a book is in satisfactory condition and that the index is a minor appendage which can be prepared by almost anyone. The usefulness of this volume is reduced considerably by a woefully inadequate index less than four pages for 232 pages of text, tables and bibliography. Many important formations are not even listed in the index and others are listed only a fraction of the number of times they occur in the text. The same is true of authors, names of fossils, and other subjects. Much of the important evidence on which arguments and interpretations are based is given in 49 pages of superb plates and their accompanying legends, yet this section is neglected entirely in the index. It is to be hoped that an adequate index will be prepared for a subsequent edition or printing. At the same time the few typographical errors and minor omissions can be remedied, such as the failure to mention either in the text or legend the temperature for which Figure 70 shows the solubility for SiO_2 and $CaCO_3$.

For textbook, reference, or for an intensive study of problems of fossil reefs by practicing geologists this treatise can be highly recommended.

EARL INGERSON

WADIA, D. N., Geology of India, Macmillan and Co., Ltd., New York 17, N. Y., xx + 531 pp., 1953, $10.00

The third edition of this well-known book was necessitated by the very great progress made in the study of the geology of India since 1937. The contributions to the economic geology and the mineralogy of the Indian region have been particularly significant. Wadia includes within the Indian region those countries "forming natural physical extensions of India proper," Pakistan, Burma, Ceylon, and parts of Tibet.

Geophysicists interested in the geology of India will find this book an indispensable companion. The book is introduced by a chapter on Physical Features which contains a discussion of the volcanoes, earthquakes, local alterations of level, and isostasy as they pertain to the Indian region. The next 23 chapters are devoted to the presentation of the stratigraphic and geologic record of the Indian region from the Precambrian to the Recent period.

A considerable amount of space is devoted to petrology. Chapter 3 is a summary of the petrologic description of the Archean system, gneisses and schists. Chapter 16 describes the Deccan Trap. Brief accounts of igneous and metamorphic rocks are scattered through the other chapters. The last two chapters of the book describe the physiography and economic geology of India.

A handy geological map in color of the Indian region is inserted in a flap at the back of the book.

GEORGE T. FAUST

GRIM, RALPH E., Clay Mineralogy, McGraw-Hill Book Co., xii + 384 pp., 1953, $9.00.

Geophysicists have good reason to be interested in this book for the clay minerals form an integral part of the Earth's crust. They are the dominant minerals of the clays, shales, and soils, and are present in varying amounts in all other kinds of sedimentary rocks. Moreover, they are present, through the agency of secondary processes, in both igneous and metamorphic rocks.

Grim has gathered together the widely scattered data on the chemistry, physics, and mineralogy of the clay minerals to prepare this book. He is very well qualified to do this for he is one of the leading contributors to the growing literature of the clay minerals. The text is well illustrated; it contains 121 figures, and is especially well documented with references to the literature.

After an introduction and two chapters on the history, classification, and nomenclature of the clay minerals the author presents a very readable account of the basic concepts of the crystal structure of the clay minerals. Thereafter follow chapters on the methods of identifying or studying the clay minerals, namely, X-ray diffraction data; shape and size - electron micrographs; ion exchange; clay-water system; dehydration, rehydration and changes taking place on heating; clay-mineral-organic reactions; optical properties; and miscellaneous properties. The book concludes with two chapters on the origin and occurrence of the clay minerals.

For those scientists interested in the physical and chemical properties of the clay minerals this text is an authoritative work.

GEORGE T. FAUST

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NOTES AND PERSONALIA

NOTES

International Geophysical Year--The period from August, 1957, to December, 1958, has been designated as the period for the International Geophysical Year by the International Council of Scientific Unions. Various Unions of the Council, including the International Union of Geodesy and Geophysics, are cooperating in this effort, and in the various countries, committees have been appointed to work out and arrange programs of research. The Committee for the United States that has been appointed by the National Research Council consists of Joseph Kaplan, Chairman, L. H. Adams, H. G. Booker, Lyman W. Briggs, G. M. Clemence, C. T. Elvey, John A. Fleming, Nathaniel C. Gerson, L. M. Gould, F. W. Reichelderfer, Elliot B. Roberts, Alan H. Shapley, Paul A. Siple, A. F. Spilhaus, Merle Tuve, A. L. Washburn, Members; and Wallace W. Atwood, Lloyd V. Berkner, J. Wallace Joyce, and William W. Rubey, ex-officio members, with Hugh Odishaw as Administrative Secretary. H. Kirk Stephenson is the Liaison Representative of the National Science Foundation. Reporters have been appointed as follows: World Days, A. H. Shapley; Meteorology, Harry Wexler; Geomagnetism, E. B. Roberts; Aurora and Airglow, C. T. Elvey; Cosmic Rays, S. A. Korff; Solar Activity, S. B. Nicholson; Ionopheric Physics, H. G. Booker; Longitude and Latitude, G. M. Clemence; Glaciology, W. O. Field; Oceanography, E. H. Smith; and Rocketry, J. A. Van Allen.

Originally the plan was initiated as the Third International Polar Year, the First having been held in 1882-1883 and the Second in 1932-1933, but as plans developed the scope extended beyond the polar areas, resulting in the present designation.

The main purpose is that during the Geophysical Year special efforts will be made to secure and interrelate geophysical data gathered all over the globe relating to the various aspects of geophysics, especially in fields in which international cooperation is essential. Suggestions for the Committee should be sent to Administrative Secretary Odishaw in care of the National Research Council, 2101 Constitution Avenue, Washington 25, D. C.

National Science Foundation predoctoral fellowships--The National Science Foundation has recently announced the award of 657 predoctoral fellowships of which 31 were in the Earth sciences, 134 in physics, 91 in the engineering sciences, and 11 in agriculture. In addition, 1355 applicants were accorded honorable mention. The number of applicants totaled 2865.

Time relations of the sediments of the ocean floor--The National Science Foundation has announced a grant to Columbia University for studies of time relations of sediments of the ocean floor. The project will be under the direction of J. L. Kulp.

Course in aerial photogrammetry--École Nationale des Sciences Géographiques of the Institut Géographique National will give a course in aerial photogrammetry from June 27 to August 7, 1954. The course is limited to 25. Inquiries and applications should be sent to the Director of the school, 136 bis, rue de Grenelle, Paris 7^{e}, France. May 15 is the closing date for applications.

The Scripps Trans-Pacific Expedition--The North Pacific expedition of Scripps Institution of Oceanography aboard the *Spencer F. Baird*, which extended through the Aleutians to Japan, has returned after four and a half months. Data were gathered on circulation in the North Pacific and Bering Sea, the distribution of plankton, the physical and chemical properties of ocean water, and temperature. Biological specimens were collected to depths of over 5000 meters. Continuous echo-sounding records were kept which revealed several new sea mounts. In Japanese water there was close collaboration with a number of Japanese oceanographers.

Eighth Pacific Science Congress--The Eighth Pacific Science Congress was held in Manila, November 16-28, 1953, with over 700 delegates from 30 countries in attendance, including about a hundred from the United States. A large number of the papers dealing with the physical sciences bore on various aspects of geophysics, and several sessions were devoted to oceanography and meteorology of the Pacific. There were symposia on volcanology, seismology, and the basement complex. A number of excursions were arranged in connection with the Congress.

PERSONALIA

Maurice L. Albertson, Professor of Civil Engineering and Head of Fluid Mechanics Research at Colorado A and M College, is in France on a Fulbright Research Grant studying various aspects of erosion, sedimentation, and hydraulic structures at the University of Grenoble and the Neyrpic Establishment. He will return to Colorado A and M. College in September, 1954.

Kenneth L. Cook, formerly of the U. S. Geological Survey, has been appointed Associate Professor and Head of the Department of Geophysics of the University of Utah, Salt Lake City, Utah. He will continue his affiliation on a part-time basis with the Geological Survey for research studies in geophysics. He has also been appointed Chairman of the Geophysics Subdivision of the American Institute of Mining and Metallurgical Engineers.

A. E. Cummings, Director of Research at the Raymond Concrete Pile Co., was elected Vice President of the Conference on Soil Mechanics and Foundation Engineering at the Third Conference held in Switzerland August 15-27, 1953.

J. W. Dixon, until recently in charge of Project Plans for the Bureau of Reclamation, has taken up duties as Assistant to the President of the Harza Engineering Co. with headquarters in Chicago.

F. M. Fryxell, Professor of Geology at Augustana College at Rock Island, Illinois, has been named as the first recipient of the Neil Miner Award for the recognition of meritorious accomplishment for stimulating interest in the Earth Sciences.

Joseph J. George, Chief of the Weather Services of Eastern Air Lines, has been named Deputy Chief of the U. S. Weather Bureau to put into effect the reorganization recommended by the Advisory Committee on Weather Services of the Department of Commerce of which Committee he was the Chairman.

Jack L. Hough, Professor of Geology at the University of Illinois, is on assignment serving as Head of the Department of Geology, Indian Institute of Technology at Karaghpur, for a period of two years. In the spring semester of 1956, he expects to be on sabbatical leave, touring the Near East and Europe.

C. E. Jacob, until recently Head of the Department of Geophysics at the University of Utah, and now Associate Professor of Geology, Brigham Young University, was on leave January-March, 1954, as consultant to government of Israel, Tel Aviv.

Terris Moore has resigned as President of the University of Alaska and has taken up duties as Director of Industrial Cooperation at the University of Maine.

Thomas B. Nolan, Assistant Director of the U. S. Geological Survey, was recently given the K. C. Li Medal and Award for his work and leadership in the Survey for a better understanding of the geological occurrence of tungsten.

Troy L. Péwé of the U. S. Geological Survey has been elected Secretary of Alaska Division of the American Association for the Advancement of Science.

M. M. Slotnick has resigned from his position with the Humble Oil and Refining Co. and has taken up duties as Consultant Geophysicist for the Standard-Vacuum Oil Co. with headquarters in New York.

Herbert C. Storey, formerly Chief of the Division of Forest Influences at the Northeastern Forest Experiment Station, has recently been appointed Chief of the Division of Forest and Range Influences Research.

H. W. Straley, III, geologist and geophysicist of Princeton, W. Va., is currently engaged in electrical and magnetic investigations of iron deposits in northern Georgia.

Hugh M. Thralls of the Seismograph Service Corporation has been elected Secretary-Treasurer of the Society of Exploration Geophysicists.

Verle L. Austin, Hydraulic Engineer with the U. S. Geological Survey in Austin, Texas, died on July 27, 1953, at the age of 57. Born at Nevinville, Iowa, he took his baccalaureate degree from the University of Kansas in 1921, and began work with the Survey in 1922, serving first at Rolla, Missouri, and later, since 1930, in Texas. Posthumously he was given the Commendable Service Award of the Department of the Interior. He became a member of AGU in 1936.

Robert Tsai-Hsing Chen, member of the staff of the Division of Agricultural Engineering at the University of Minnesota, died November 3, 1953, at the age of 32. He was born in Shanghai, China, and took his baccalaureate degree from National Wu-Han University in 1944, and his master's degree from the University of Minnesota in 1951. He had been doing research work in determining a measure of need for supplementary irrigation and on a study of soil permeability. He became a member of AGU in 1952.

Ralph E. Digman, Assistant Professor of Geology at the Harpur College, State University of New York, died on December 20, 1953, at the age of 33. He was born in Milwaukee, Wisconsin, and took his baccalaureate degree from Lawrence College in 1942, his master's degree from Yale in 1943, and his doctorate from Syracuse in 1950. From 1944 to 1947, he was an Instructor at Wesleyan University, and took up duties at Harpur College in 1947. He became a member of AGU in 1948.

Robert Franklin Ewald, Hydraulic Engineer for the Aluminum Company of America in Pittsburgh, died July 17, 1953, at the age of 72. He was born in Fairchild, Wisconsin. He attended and taught at the University of Wisconsin, and was awarded a professional degree in Civil Engineering in 1915. He devoted most of his adult live to service with Alcoa, beginning in 1912 on work in Tennessee. In 1917, he moved to Pittsburgh, which was his official headquarters until his death. He was the author of many project reports bearing on hydrology, hydraulic engineering, and the development of water power. He had been a member of AGU since 1939.

Nicholas H. Heck, Captain, U. S. Coast and Geodetic Survey, retired, died December 21, 1953, at the age of 71. He was born in Heckton Mills, Pa., and received his baccalaureate degree from Lehigh University in 1903, then entering the course in civil engineering and taking his engineering degree in 1904. Later he was awarded honorary doctorates by his Alma Mater and by Fordham University. His entire professional career was with the Survey except for a period during the First World War, and for 20 years he was the Chief of the Division of Terrestrial Magnetism and Seismology. He was an authority on seismology, and his book, Earthquakes, is considered one of the classics in the field. He retired in 1945. He served as President of the Union from 1935 to 1938, and earlier had served as Vice President and President of both of the Sections of Seismology and of Terrestrial Magnetism and Electricity, and President of the Section of Oceanography. He was named as the Fourth Recipient of the William Bowie Medal in 1942. He had been a member of AGU since 1923.

Earle W. Johnson, President of the General Geophysical Co., died August 11, 1953, at the age of 51. He was born in Denison, Texas, and attended the University of Texas and Texas A and M College. His early professional work was as Party Chief of a seismic field crew, and included the interpretation of results. In 1935, he became President of the General Geophysical Co., engaging in various types of geophysical exploration work. He became a member of AGU in 1952.

Kent K. Kimball, Consulting Geologist of Tulsa, Oklahoma, died August 9, 1953, at the age of 61. He was born in Lincoln, Nebraska and took his baccalaureate degree from the University of Nebraska in 1917. After brief duty with the Empire Gas and Fuel Co. he worked for the U. S. Geological Survey from 1918-1923, when he joined the Mid-Kansas Oil and Gas Co. In 1933 he established his office as consulting geologist. He had been a member of the AGU since 1947.

Frank B. Littell, Professor of Mathematics and Captain, U. S. Navy, retired, died March 28, 1951, at the age of 82. He was born at Scranton, Pa., took his baccalaureate degree at Wesleyan University in 1891, and was awarded an honorary doctorate in 1919. He took his master's degree from Columbian College (now part of George Washington University) in 1894. Except for a year of high school teaching early in his career, his professional life was in the service of the Navy, beginning as a Computer with the Naval Observatory in 1891. He was active as participant and organizer in various eclipse expeditions. In 1913-14, he was a member of the U. S. party working on problems of Washington - Paris longitude determinations by radio. He served as Chairman of the Executive Committee of the Naval Observatory from 1909 until 1933 when he retired. He had been a member of AGU since 1934.

Robert A. Millikan, Emeritus Professor of Physics and formerly Chairman of the Executive Council, California Institute of Technology, died December 19, 1953, at the age of 85. He was born in Morrison, Illinois, and took his baccalaureate degree in 1891 and his master's degree in 1893 from Oberlin. He received his Ph. D. from Columbia in 1895, and the following year studied in Berlin and Göttingen. He was the recipient of many honorary degrees, as well as numerous other honors and awards, the chief of which was the Nobel Prize in Physics in 1922. He began his career at Oberlin. In 1896 he became a member of the staff of the Physics Department of the University of Chicago where he remained until 1921. He took up duties at California Institute of Technology at that time, retiring in 1946, but becoming Vice President of the Board of Trustees. He was the author of many books and other publications, and though an authority in many fields of physics, he is most frequently thought of for his pioneer work on cosmic rays. He was one of the original members of AGU.

Leonard J. Neuman, Consulting Geophysicist, died December 18, 1953, at the age of 53. Born at Little Falls, Minnesota, he took his baccalaureate degree at Montana State College in 1923, and his master's degree at the University of Oregon in 1925, subsequently doing work towards his doctorate at the University of California. He taught at the University of Santa Clara from 1928 to 1930, when he became Director of Geophysical Research with the Texas Company, and after a tour of similar duty with the Petty Geophysical Co. from 1933 to 1936, he established his own firm. He had been a member of the AGU since 1944.

John J. O'Neill, Science Editor for the New York Herald Tribune, died on August 30, 1953, at the age of 64. He started his career as a printer, and through night-school, correspondence school, and independent study, became a serious student of science. His lucid style gave him excellent opportunity to relay to the public the many important developments in various fields of science, and he received a number of prizes and awards for his excellent work in scientific reporting during the last two decades. He had been with the Herald Tribune since 1934, and joined the AGU in 1948.

Louis A. Scholl, Jr., Geophysical Consultant of Houston, Texas, died September 22, 1953, at the age of 67. He was born in Pittsburgh, Pennsylvania, and received his baccalaureate degree from Carnegie Institute of Technology in 1910. He worked for the Bureau of Mines at Urbana, Illinois, until 1914, entered Columbia University from which he took his master's degree in 1916. He entered the service of Producers Oil Co. (now the Texas Company) and from 1920 to 1925 supervised their geological exploration in South America, when he returned and enrolled for graduate work at the University of California. In 1927, he resumed his work with the Texas Company, and in 1929 was made Chief of the Geological Department in Houston. In 1945, he became Manager of the Geophysical Division, and became Geophysical Consultant in 1950. He retired in December, 1952. He had been a member of the AGU since 1932.

LeRoy K. Sherman, Consulting Engineer of Chicago, died on January 5, 1954, at the age of 84. He was born at Eastham, Mass., and took his baccalaureate degree from Massachusetts Institute of Technology in 1892. His early career was devoted to diverse engineering work on the Chicago Drainage Canal and with various railroads. He became the Assistant Chief Engineer on the design and construction of the North Share Channel and Calumet Canal, and a member of the Illinois Rivers and Lakes Commission. From 1918 to 1920, he was with the U. S. Housing Corporation. Following this, he became President of the Randolph-Perkins Co., Engineers, of Chicago. Following his retirement in 1934, he established a consulting practice. His work in hydrology and on hydrologic reports is extensive but he is perhaps best known for his invention and development of the unit graph for hydrograph analysis. He had been a member of the AGU since 1932, serving the Section of Hydrology in many capacities, and as President from 1936-1939.

Owen F. Thornton, Vice President of the Louisiana Land and Exploration Company, died July 15, 1953, at the age of 36. He was born at Wewoka, Oklahoma, and took his baccalaureate degree in 1936 and his master's degree in 1937 from Oklahoma A and M College. During his brief and active career, he had served as Chairman of the Gulf Coast Section of the American Institute of Mining and Metallurgical Engineers. He was the representative of the Corporation Membership of the Louisiana Land and Exploration Co.

Transactions, American Geophysical Union Volume 35, Number 2 April 1954

MINUTES OF EXECUTIVE COMMITTEE MEETING, AMERICAN GEOPHYSICAL UNION

Meeting of November 28, 1953

The meeting was called to order at 13h 35m in the Board Room of the National Research Council - National Academy of Sciences Building, 2101 Constitution Avenue, Washington, D. C., by President James B. Macelwane.

Present--Twenty-eight persons were present, namely: L. H. Adams, John M. Adkins, L. R. Alldredge, Wallace W. Atwood, Jr., Ralph R. Bodle, Walter H. Bucher, James J. Capello, Felix Chayes, F. L. Culley, E. A. Eckhardt, Maurice Ewing, W. F. Foshag, Ross R. Heinrich, H. H. Hess, William E. Hiatt, W. C. Jacobs, H. R. Joesting, J. W. Joyce, Walter D. Lambert, J. B. Macelwane, J. P. Marble, Jerome Namias, F. W. Reichelderfer, W. W. Rubey, A. N. Sayre, Waldo E. Smith, J. T. Wilson, and R. N. Wilson. The following were excused: Fred Anderegg, Robert Balk, Hugo Benioff, J. Bjerknes, Francis Birch, Harry F. Blaney, Perry Byerly, P. E. Church, Jno. A. Fleming, R. H. Fleming, B. Gutenberg, C. O'D. Iselin, Ray K. Linsley, W. H. Munk, B. O'Brien, A. C. Redfield, M. O. Schmidt, H. T. Stetson, V. Vacquier, F. J. Veihmeyer, and H. G. Wilm.

Approval of minutes--The minutes of the Executive Committee meeting on May 6, 1953, published in the August, 1953, issue of the Transactions, pages 656-668, were approved.

General Secretary's Report

This Report covers the various official activities of your General Secretary from July 1, 1953, the date of his assumption of office, to November 10, 1953. To assure continuity with the last report of his predecessor, which was dated as of May 1, 1953, some matters dating before July 1, 1954, are included, and a few items concerned with the last two weeks are also included.

As a matter of convenience we have divided this Report into four sections: (1) publications; (2) activities of the Union in its own domain; (3) activities of the Union as the Committee on Geophysics of the National Research Council and as the American Committee of the International Union of Geodesy and Geophysics; and (4) sundry news items of interest.

General Activities

Publications--Three numbers of the Transactions have been published since the last Report of the General Secretary, those for June, August, and October, 1953, being pages 353 through 832 of Volume 34. The total issue per number is now 5600. The June and August numbers were, as in past years, the responsibility of the previous Editorial and Publication Committee. For those interested in a breakdown of these three numbers into subjects, copies of them are available. H. W. Fairbairn has succeeded Anna Hietanen Makala as editor for Tectonophysics, and K. H. Beij has succeeded Jno. A. Fleming as Adviser to the Committee. Your General Secretary, in his capacity as Editor, is deeply grateful for the cooperation of all his associates. The character of the material published recently is completely up to the high standards which the Union sets in carrying out this most important of its duties. The number of papers which this Committee feels necessary to turn down remains about constant, and we do not seem to be troubled with "crank" papers to a greater extent than in the past.

The History of the AGU by Dr. Fleming, which was originally planned for publication in the October issue was first postponed until the December issue, and has had to be further postponed until the February, 1954, issue, because of delay in the receipt of corrected proof.

The problem of our back-log of papers is becoming of increasing embarrassment to the Editorial and Publication Committee. As of November 13, 1953, the date of the last meeting of the Committee, the backlog beyond the December issue was 110 papers. This compares with 123 in September 18, 1953; 95 in November, 1952; 85 in November, 1951; 63 in November, 1950; 67 in November, 1949. The difference between 110 and 123 papers is in line with the seasonal trend so we are making no real progress in catching up. The trend in backlog is distinctly upward, and we now have close to a year's gap between submission of a manuscript and its publication. This is undoubtedly too long. As said before, the quality of papers published remains high, so we cannot hope to improve matters by being harder-boiled. If we follow the policy recently suggested, and one which appeals to your Editor, of publishing more papers on geochemical topics, we may expect a further increase in the acceptable material submitted. This problem of what to do about the demands on publishing space is one that is faced by all scientific periodicals, and is not our own private headache. This important question has been put near the head of the agenda of this meeting, and various possible solutions, all of which will cost money, will be proposed. It calls for our careful study.

Memberships--As regards our general operations, our membership as of November 10, 1953, was 5013. This represents a net gain of 13 since May 1, 1953, as shown in the following summary.

Membership, May 1, 1953	5000	
New members, May 1, 1953 - Nov. 20, 1954	233	
Reactivated	3	5236
Resigned	25	
Dropped (tentative)	179	
Inactive	4	
Deceased	15	223
Membership as of Nov. 25, 1954		5013

It should also be pointed out that the activities of the new Committee on Membership are just getting under way.

We regret extremely to announce the deaths of the following members of the Union, of which we have learned since the last such report: Eric R. Miller (April 8, 1952), James B. Wood (July 9, 1952), W. M. Jones (March 15, 1953), Harry Bouchard (March 21, 1953), William P. Creager (April 4, 1953), A. O. Lenschner (April 22, 1953), Elmer H. Finch (April 29, 1953), Robert W. Gay (May 8, 1953), Joseph Hollister (May 8, 1953), A. A. Jakkula (May 30, 1953), Guenter Loeser (July 30, 1953), Marcel E. H. Schlumberger (August 20, 1953), Frederick E. Wright (August 25, 1953), Scotland G. Highland (October 25, 1953), and Harry A. Marmer (November 5, 1953).

Additions to the list of Corporation Memberships continue slowly, but steadily. A modest increase in our funds from this source is to be expected as time goes on.

Financial report--Financially, the Union is in about its usual condition for this time of year. Most important, we appear to be keeping well within our budget limits. Our net cash balance at the Riggs National Bank as of November 1, 1953, was $8367.36. This compares with $7978.01 a year earlier. This balance will continue to shrink until the end of the year, following which it will rise sharply with the receipt of 1954 dues and subscriptions. It should be noted that March represents about our high-water mark financially and that the June 30 statement always reflects a more favorable than realistic situation. By now we have spent a considerable part of our allotment and have not yet received much of our income.

The Committee on Audit has the official financial statement for the year ending June 30, 1953 (see Appendix 1).

The three officers of the Union who are authorized to sign checks, the General Secretary, the President, and the Vice-President, are now bonded under the general bond of the National Academy-National Research Council.

Staff--The office staff as of today consists of: James J. Capello, Assistant to the Executive Secretary and Assistant Editor; Miss Irene Dantine, Clerk-Stenographer; Mrs. Elsie Davis, Clerk-Typist; Mrs. Nancy Ing, Electromatic Operator and Assistant in Editorial Work; all under the direction of the Executive Secretary, Waldo E. Smith.

Various activities--A. F. Spilhaus and D. B. Lawrence represented the Union at the Fourth National Conference for UNESCO held in Minneapolis on September 15-17, 1953. Their report will appear in the Transactions (see Feb., 1954, pp. 188-189). J. T. Wilson represented the Union at the inauguration of the President of Wayne University at Detroit.

The 31st Regional Meeting was held at Minneapolis on August 31, 1953. In connection therewith the North-Central Region of the Union was organized. Statutes and By-Laws for this new Region have been prepared by the local officers, and are under study by the Committee on Statutes and By-Laws (see Appendix 2).

A group in Hawaii has been organized as the Geophysical Society of Hawaii, and their official relation to the Union is under consideration.

We have used our influence with some success to aid Dr. Wadati in Japan to continue volcanologic and other geophysical studies at Mt. Asama, where there was some months ago a possibility that the area might be used for military purposes.

Arrangements will shortly be discussed with the proper authorities of the Carnegie Institution of Washington looking to the continuation of existing arrangements for the use by us of space in their administration building at 1530 P Street, N. W. So far as we now know, the matter will be arranged. The question of a permanent home is being kept in mind by your officers.

Activities in relations to the National Research Council

The resolutions adopted by the Union at the last Annual Meeting were duly sent out to the appropriate parties. A number of favorable responses have been received, as is usual. This technique seems to be effective.

The annual grant of $400 from the NRC has been authorized, but not yet utilized. We plan to use this as part payment of the next bill for printing Transactions.

As regards our functions as the Committee on Geophysics of the National Research Council, the situation is somewhat mixed, at least from the official point of view. The recent and continuing reorganization of the National Academy of Sciences - National Research Council leaves this somewhat uncertain. This is naturally a matter of the utmost importance, and occupies an important position in the agenda of this meeting. Meanwhile, your General Secretary continues to assume that he should act as in the recent past, pending official advice to the contrary.

We have recently received about $500 from the NRC as a first reimbursement to the Union for funds expended in connection with the NAS-NRC-AGU contract with the Air Force for a Conference next spring on atmospheric electricity. Arrangements for the time and place of the conference have been made, and the program is being drawn up.

The Tenth General Assembly of the International Union of Geodesy and Geophysics will be held in Rome, Italy, from September 15 through September 29, 1954 (changed to September 14-25, 1954). A preliminary announcement has been sent out by General Secretary Laclavere, and we have just received the formal invitation from the Italian National Committee. A start has been made on the personnel of the delegation from the United States, both official and unofficial, but those most interested have in many cases appeared to be reluctant to suggest themselves as delegates. Nominations to the NRC should be settled this meeting, if possible. The National Science Foundation has set January 1, 1954, as the closing date for application for travel grants to attend this Assembly. Those who plan to attend the Assembly at their own expense should make travel arrangement as soon as possible, as accomodations in Rome and on or over the Atlantic may be crowded.

Future meetings of the Union or its Regions will be noted by the Committee on Meetings. We have been informed that the spring meetings of URSI will be held in Washington at National Bureau of Standards, and of the AMS in Baltimore, respectively, just before and just after ours.

Items of general interest

The following news items may be of some interest: A Mid-Century Conference on Resource has been organized by a group involving many of our members. NRC has set up an International Relations Center for Scientists and Engineers; also NRC has prepared a list of foreign scientific visitors, with their dates and schedules. Of the recent NSF awards to support basis research, at least ten bear heavily on geophysics. Three or four of the recent AEC contracts lie in geophysics. The American Society of Photogrammetry, which some time ago discussed informally the setting up of a joint office with us has made other arrangements, and now occupy private premises together with the Congress on Surveying and Mapping.

To save time, some matters that might also appear in this Report that are also listed on the Agenda are not repeated here.

John Putnam Marble, General Secretary

Action on the General Secretary's Report--The report was accepted.

Committee appointments--The President reported that all of the Chairmen of the Standing Committees and all but one of the Chairmen of the continuing Special Committees have been appointed, and the membership of the Committees, while not complete, is well advanced.

International Matters

Tenth General Assembly of the International Union of Geodesy and Geophysics--There was discussion of the nominees for the State Department delegates to the Assembly, the Executive Secretary outlining the previous policy, namely, initially suggesting the four officers of the Union and the eight Presidents of the Sections. As Chairman of the National Committee from the United States, the President is normally the first nominee for the Chairman of the delegation. Similarly, the President of a Section, as the Chairman of the American National Committee of the respective association, is usually the most obvious initial nominee as the Chief Delegate to the Association unless, as is the case in Geodesy, someone else is specifically named by the Section. A preliminary letter relating to these nominees was sent out to the Executive Committee on July 24, 1953, and a second one on October 6, and on the basis of the responses, the following were offered as a basis for discussion: President of the Union, James B. Macelwane (suggested as Chief Delegate); Other officers of the Union, Maurice Ewing, John Putnam Marble, and Waldo E. Smith; Geodesy, Charles A. Whitten; Seismology, Ross R. Heinrich; Meteorology, Phil E. Church; Terrestrial Magnetism and Electricity, Victor Vacquier; Oceanography, Richard H. Fleming; Volcanology, Felix Chayes; Hydrology, Harold G. Wilm; and Tectonophysics, Louis B. Slichter. It was pointed out that under tentative plans, as in 1951, a substantial delegation from the NAS-NRC would also be designated, and all scientists and technologists from the United States who attend would be accredited by the AGU as the National Committee from the United States, or the NRC as the official adhering body.

It was noted that the Department of State has received the official invitation, and has sent word to the various government agencies requesting suggestions for the delegation, word of these to be in the hands of W. W. Atwood, Jr., Director of the Office of International Relations, by December 20, 1953. Atwood pointed out that though the funds for travel grants to this Assembly of the National Science Foundation will be far from adequate and that State Department funds have been curtailed. The delegation should be named from the total field of Geophysics that would reflect highest credit to the United States, and that funds for their attendance will need to be raised from some source. It was mentioned that the meeting falls in the next fiscal year, and that funds are as yet unappropriated. He felt that we should nominate a list of 12 with three alternates, and possibly we would have a delegation of ten, the names of which we should send to the Department of State early in January. He suggested tentative nomination of the group cited, then after the receipt of nominations by agencies, these might be considered with the aim of naming 15 to be offered to the State Department.

It was moved, seconded, and approved that those cited be offered to the NRC as a preliminary, informal list and further that the officers of the Union be authorized to arrange for alternate delegates with the various Sections of the Union, and to make official, on behalf of the Union, the appointment of people as delegates from the State Department and the NRC. Atwood also outlined the organization of the International Council of Scientific Unions, supplying an organization chart. He mentioned the importance of briefing the delegates to the Rome meeting before their departure.

It was agreed that about 30 more names would be offered to the NRC as additional NRC delegates.

Word had come of the agenda for all associations, but no details of the programs have been received. Those planning to go the Assembly should begin making travel arrangements at an early date. It was noted that General Secretary Laclavere of the IUGG had received word from Air France that would supply a specially chartered plane that will hold 64 for about $12,000 per one-way trip.

International Geophysical Year--It was reported that the Committee on the Geophysical Year for the United States headed by Joseph Kaplan has been very active. Atwood advised that a secretariat under the direction of Hugh Odishaw has been set up by means of a grant from the National Science Foundation.

The place of geochemistry in the AGU and the IUGG--General Secretary Marble mentioned that one of the recent important phenomena in the interrelations of the sciences has been the increase in the use of the techniques and background of the chemist in helping to solve the problems of our understanding of the Earth -- using this in its broadest sense. The AGU has always welcomed the geochemists, indeed, there was proposed recently a change in the name of the Section of Volcanology to Volcanology and Geochemistry or a similar title. We have also welcomed the presentation of geochemical papers at our Annual Meetings and their publication in the *Transactions*. Any great increase in such publication will either require more funds, which we do not have, or the cutting down of papers in other of our fields, which we do not welcome. It should further be pointed out that in this country the American Chemical Society seems to show no interest in publishing such papers; while on the international scale the International Union of Chemistry has taken geochemistry under its wing, with no interest in this field shown by the IUGG. It was the general feeling that we should continue our present policy of encouragement of the publication of papers in geochemistry, and including them in our program, chiefly in relation to Volcanology.

Reports of Standing Committees

Editorial and Publications--Chairman Marble referred to his earlier report regarding increasing backlog of unpublished papers. There was a brief discussion of this and suggestions were offered for the consideration of the Committee.

Meetings--Chairman John Adkins announced the following meetings: Thirty-First Regional Meeting in Boston, Mass., in connection with the meeting of the American Association for the Advancement of Science, December 28-30, 1953; Thirty-Second Regional Meeting, University of Southern California, Los Angeles, California, January 29-30, 1954; and Thirty-Fifth Annual Meeting, Washington, D. C., May 3-5, 1954. There may be a meeting in the Kansas City area in late summer. The AAAS regional group has invited our Pacific Southwest group to meet with them in the Washington - Oregon area, but this is outside of this region's activities and there is thus far no organization of the Pacific Northwest Region. AAAS will hold its national meeting in the San Francisco - Berkeley, California, area in late December, 1954, and has invited AGU to join. The matter has been referred to the Regional Committee.

The tentative schedule set up for the Thirty-Fifth Annual Meeting seemed acceptable as a working basis.

Audit--Chairman A. Nelson Sayre noted that the books of the Union to June 30, 1953, had been audited and found in good shape as shown in the report published below as Appendix 1. The report was accepted.

Statutes and By-Laws--Chairman K. Hilding Beij was absent, but R. R. Bodle (who with Jno. A. Fleming are the other members of the Committee) reported as follows: Proposed By-Laws for the North Central Regional Branch of the American Geophysical Union were considered by this Committee (and also the Executive Secretary of the Union) and certain changes were recommended. These changes were incorporated in the By-Laws as adopted at a meeting in Minneapolis on August 31, 1953. A copy of the adopted By-Laws is attached to this report. Your Committee recommends that the By-Laws of the North Central Regional Branch, herewith submitted, be approved by the Executive Committee of the American Geophysical Union. The By-Laws are presented in Appendix 2.

Cosmic Terrestrial Relationships--Chairman Stetson presented a summary of the report shown as Appendix 3. This was accepted.

Tsunamis--On the recommendation of retiring Chairman Martin A. Mason that his Committee has completed the work for which it was established, it was agreed to discontinue this Committee.

Geophysical and Geological Study of Ocean Basins--Retiring Chairman Harry H. Hess reported that he felt that this Committee had largely fulfilled the work for which it was established, and recommended that it be discontinued, its remaining functions to be undertaken by the Committee on Geophysical and Geological Study of Continents. This was approved.

Surveys and Maps--On the written recommendation of retiring Chairman G. Medina that this Committee has completed the work for which it was established, it was agreed to discontinue this Committee.

Relations of the AGU with the NRC--Chairman F. W. Reichelderfer presented the report shown as Appendix 4 explaining that this was as of June 30, 1953, because the Committee had essentially completed this work by that time, but certain more recent developments alter the picture in some degree. He further pointed out that the Committee was not one empowered to negotiate, but only to study and recommend and that it has done. The Committee found important differences in opinion. Now the decision as to the next step is up to the Executive Committee. He felt that a high-level committee empowered to negotiate an understanding should be appointed. There was extensive discussion of the report, and the problems involved by the changes, both in AGU and the NRC, since AGU was brought into existance in 1919.

Chairman of the National Research Council, W. W. Rubey, pointed out the three aspects of the AGU: (1) that it functions in some regards as a large national scientific society with membership in the thousands, with meetings and with publications; (2) that it serves as the American National Committee for the IUGG; and (3) that it was established as the Committee on Geophysics of the NRC. As the first aspect has grown, the need of the NRC for a Committee on Geophysics has correspondingly declined, but it is now continuing as such only in a nominal way. Ordinarily such a committee is established in the early stages in intradisciplinary activity, and that in the course of time, the activity finds a home in one of the eight divisions. He emphasized that the AGU must continue to carry on the functions of the U. S. A. National Committee of the IUGG.

Past President Walter H. Bucher spoke about the differences of the AGU in comparison with the usual scientific society. The latter is a group of those of a strong mutuality of interests, while the former is an attempt to integrate several such groups. He mentioned the difficulty of any attempt of the newly reorganized Division of Earth Sciences to attempt to add geophysics to its former grouping of geology and geography, ideal as that may seem.

After further extensive discussion, it was moved by Marble, seconded and approved that the President be authorized to appoint a committee to confer with appropriate officers of the NRC with power to negotiate, arrive at an understanding, and report back to the Executive Committee for approval, and that the report of the previous committee be accepted with thanks.

Affiliated Organizations

American Geological Institute--E. A. Eckhardt, one of our two representatives on the Board of the Institute mentioned that at a meeting of the Board in Toronto, they adopted a new Constitution which will be submitted to the constituent organizations for ratification. It had also passed resolutions with respect to operations relating to the Glossary, the Scientific Register questionnaire, Geological Abstracts, and other matters.

Adjournment--The meeting adjourned at 17h 47m.

John Putnam Marble, General Secretary
Waldo E. Smith, Executive Secretary

APPENDIX 1--REPORT OF THE COMMITTEE ON AUDIT

Fiscal Year July 1, 1952 to June 30, 1953

A. Nelson Sayre, Chairman
A. G. McNish R. H. Weightman

Your Committee on Audit has examined the books of the American Geophysical Union for the fiscal year ending June 30, 1953, and finds them in agreement with the statement of the Union's finances supplied by the General Secretary, which is attached.

At the beginning of the current fiscal year the Cash Assets of the Union amounted to $16,204.07. These assets consisted of $14,960.01 held as Cash Reserve, $1,180.91 in the Robert E. Horton Fund, and $63.15 in the William Bowie Medal Fund. The three Funds are carried in a single account in the Riggs National Bank. The Permanent Fund amounting to $7,291.06 consisted of $2,368.00 invested in Series "F" Bonds and $4,923.06 on deposit in the Northwestern Federal Savings and Loan Association. (See Transactions, Volume 33, page 941, in December, 1952, for Statement of Assets and Liabilities as of June 30, 1952.)

The receipts for the year totalled $47,402.89, while the expenditures totalled $46,503.82; thus the Liquid Assets were increased by $899.07. It was found possible to increase the Permanent Fund

Operating Statement

(Fiscal year ending June 30, 1953)

Receipts			
Grant			
National Research Council			$ 400.00
Income			
Dues, 1950 and earlier	$ 328.50		
1951	415.00		
1952	4,301.84		
1953	28,205.75		
1954	95.80		
1955 et seq.	21.00		
Corporation Memberships	1,500.00		
Life Memberships	200.00	$35,067.89	
Sales of publications			
Transactions	$ 6.709.45		
Reprints	2,538.18		
Index of *Transactions* (1920-1944)	254.10		
Miscellaneous	125.00	9,626.73	44,694.62
Bibliography of Hydrology (balance on contract)			1,397.43
Contributions to the Permanent Fund			457.08
Interest on Permanent and Emergency Funds			198.00
Miscellaneous			255.76
			$47,402.89
Disbursements			
Publishing *Transactions*			
Printing		$ 9,994.57	
Preparing master copy		9,174.58	
Honoraria to editors		1,350.00	
Mailing		954.88	$21,474.03
Reprints			1,905.73
General expenditures (office of the Union)			
Salaries		$14,028.68	
Stationery and supplies		937.74	
Postage and communications		1,437.19	
Office equipment		241.34	16,644.95
Expenses, meetings			
Annual meeting		$ 639.24	
Regional meetings		170.38	809.62
Expenses, Sections			
Terrestrial Magnetism and Electricity		$ 3.00	
Oceanography		14.97	
Hydrology		8.90	26.87
Expenses, Committees (Membership Committee, $782.15; other, $2.83)			784.98
William Bowie Medal			13.70
Directory (Membership List)			1,742.15
Travel			179.95
Air Force Contract			78.67
Miscellaneous			45.17
Investments: (1) Deposited with Northwestern Federal Savings and Loan Assn. as part of Permanent Fund $1,600; plus interest July 1, 1952 to June 30, 1953, $170.31; total $1,770.31; (2) deposited with Prudential Building Assn. as part of Emergency Fund $1,000.00, plus interest August 1, 1952 to June 30, 1953, $27.69, total $1,027.69			2,798.00
			$46,503.82

Excess of receipts over disbursements

Receipts	$47,402.89	
Disbursements	46,503.82	
Increase in liquid funds		$ 899.07

Statement of assets and liabilities as of June 30, 1953

Assets			
Cash Reserve	$15,922.23		
Robert E. Horton Fund	1,180.91	$17,103.14[a]	
Permanent Fund			
Series F bonds purchased prior to July 1, 1948 (maturity value $3,200), at cost	$ 2,368.00		
On deposit in Northwestern Federal Savings and Loan Assn. as shown for July 1, 1953	6,693.37	9,061.37	
Emergency Fund			
On deposit in Prudential Building Assn. as shown for July 1, 1953	$ 1,027.69	1,027.69	$27,192.20
Bills Receivable			
Dues			
1953	$ 3,779.68		
1952 and 1953	1,292.00	$ 5,071.68	
Publications			
Transactions (including subscriptions)	$ 376.67		
Reprints	204.28		
Miscellaneous	24.00	604.95	5,676.63
Air Force Contract Receivable			78.67
			$32,947.50
Liabilities			
Bills payable and advance payments			
Dues in advance (1954 et seq.)		$ 125.30	
Subscriptions in advance (1954 et seq.)		134.35	
Reprints paid in advance		68.00	
Miscellaneous (mainly stationery and supplies)		166.43	$ 494.08
Surplus			32,453.42
			$32,947.50

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[a] Riggs National Bank statement of June 30, 1953	$20,582.17
Less checks outstanding	3,479.03
Net balance June 30, 1953, as above	$17,103.14

by additions to our account in the Northwestern Savings and Loan Association of $1,770.31 in Cash and Accumulated Interest, making a total of $6,693.37 as of July 1, 1953. This amount includes a total of $457.08, graciously contributed to the Permanent Fund by individuals during the year. In accordance with the desires of the Executive Committee an Emergency Fund was established during the year by deposit in the Prudential Building Association. Including Earned Interest, this Fund amounted to $1,027.69 as of July 1, 1953.

At the end of the year the Cash Assets of the Union were $17,103.14, an increase of $899.07. Of this amount $1,180.91 was credited to the Horton Fund. The Bowie Medal Fund having been reduced to $49.45 is no longer carried as a separate account, in accordance with instructions of the Executive Committee.

APPENDIX 2--BY-LAWS FOR THE NORTH CENTRAL REGIONAL BRANCH, AMERICAN GEOPHYSICAL UNION

(Adopted by the Region, August 31, 1953)

Preamble

The North Central Regional Branch of the American Geophysical Union, embracing the membership resident within the states of Minnesota, Iowa, Missouri, North Dakota, South Dakota, Nebraska, and Kansas, and contiguous Canadian provinces, is hereby established under the authority of Article 10 of the Union Statutes. The purposes of the Regional Branch shall be to promote the aims and objectives of the American Geophysical Union, to foster an effective program of scientific activity within the broad field of Geophysics, and to render more effectively to the constituent membership the services envisioned in the founding of the parent organization. These purposes shall be accomplished by means of periodic technical meetings and such other pertinent activities within the Region as the membership may elect to sponsor. The North Central Regional Branch shall be subject to the Statutes and By-Laws of the American Geophysical Union. The functions of the Branch shall be performed in accordance with the following By-Laws.

(1) Membership--Members in any grade in any Section of the American Geophysical Union resident within the territory comprising the North Central Region shall be members of the Regional Branch.

(2) Administration--The functions of the Regional Branch shall be administered by a Regional Committee consisting of representatives of the respective Sections electing to participate in the activities of the Branch. Each Section shall be entitled to representation in accordance with the following schedule:

Numbers of members enrolled in Section	Representation on Regional Committee (not more than)
1 to 50	1
51 to 100	2
101 to 150	3
over 150	4

The first election of committee members shall be held at the technical meeting in Minneapolis, Minnesota, August 31, 1953. The incumbent Committee shall conduct subsequent elections by mail ballot prior to June 30, 1956 and prior to the expiration of each succeeding triennium. Thenceforth, the term of office for members of the Committee shall be three years. Under the direction of the retiring Chairman the new Committee shall elect a Chairman and Secretary-Treasurer whose terms of office shall be one year. Each year during its tenure the Committee will elect a new Chairman and Secretary-Treasurer, but the Chairman shall not be eligible to succeed himself. The Chairman of the Regional Committee is authorized to convene the Committee for the purpose of conducting pertinent business. Three members of the Committee present shall constitute a quorum. The Chairman is authorized also to convene open business meetings of the Regional membership in conjunction with announced technical meetings in which case the members present will constitute a quorum. The Chairman of the Regional Committee shall not have a voice on any matter of business brought up for vote except in the event the voting body casts a tie.

(3) Subcommittees--The Regional Committee may designate Subcommittees, if it deems desirable, to carry out the functions of the Branch. Active Sections in the Region are authorized to elect in addition Section Committees to facilitate the work in their respective fields.

(4) Vacancies--Appointments to fill vacancies in the Regional Committee shall be made by the Chairman of the Regional Section Committee concerned or, if there is no such committee, by the President of the National Section.

(5) Meetings--Technical Regional meetings shall be arranged by the Regional Committee at times and places it deems appropriate and desirable. Any Section Committee is authorized to take part in meetings planned by the Regional Committee and also to hold independent technical section meetings. All Regional meetings are subject to the approval of the Executive Committee of the Union.

(6) Finances--Funds to defray the expenses of meetings and other operations of the Regional Branch shall be derived from registration fees levied upon members attending technical meetings. Voluntary contributions and gifts donated to and for the exclusive use of the Regional Branch may be received and disbursed by the Regional Committee.

(7) Reports--The Regional Secretary shall keep the Executive Committee of the Union informed of current activities and shall submit a report of the year's activities to the General Secretary of the Union as soon as possible after June 30 of each year.

(8) Amendments--Amendments to these By-Laws may be enacted by a majority vote of the members who cast mail ballots on any question or who participate in announced business meetings of the Regional Branch. The By-Laws of the Regional Branch, and any amendments thereto, shall conform to the Statutes and By-Laws of the American Geophysical Union, and shall be subject to the approval of the Executive Committee of the Union.

APPENDIX 3--INTERIM REPORT OF THE SPECIAL COMMITTEE ON COSMIC-TERRESTRIAL RELATIONSHIPS

Harlan T. Stetson, Chairman
E. O. Hulburt, Vice Chairman

Ross Gunn	Robert R. McMath	W. T. Thom, Jr.
Serge A. Korff	D. H. Menzel	H. W. Wells
	Herbert Riehl	

At the request of President Macelwane, the Special Committee on Cosmic-Terrestrial Relationships is being continued, with membership as noted above.

Korff reports that he and his group during the summer of 1953 have established a Cosmic Ray Observing Station on the summit of Mt. Wrangell, in Alaska at an altitude of 14,000 ft which is reached by air. There is in operation at the present time a neutron monitor operating at sea level in Alaska. The group has also completed a series of cosmic ray neutron flights at the geo-magnetic equator. These data will be compared with those made last summer near the pole.

Menzel reports progress of the High Altitude Observatory in Colorado and the new Solar Observatory in New Mexico where he was active during the summer.

Riehl reports that from July to October, 1953, a University of Chicago group visited the Fleet Weather Central, Miami, Florida, under the auspices of the ONR for a special study of weather below the tropopause over the Atlantic and North America with special emphasis on the relation between temperature zones and the tropics. The purpose is to extend our knowledge of tropical storms as related to daily variations on the solar disc. Solar information was furnished by the High Altitude Observatory at Boulder, Colorado. The data obtained are now being evaluated at Chicago.

APPENDIX 4--REPORT OF THE SPECIAL COMMITTEE ON RELATIONSHIPS WITH THE NATIONAL RESEARCH COUNCIL

(as of June 30, 1953)

F. W. Reichelderfer, Chairman

L. H. Adams	Walter H. Bucher
K. Hilding Beij	Jno. A. Fleming

The Executive Committee in its meeting November 7, 1952 [see Transactions AGU, v. 33, no. 6, p. 938], authorized President Bucher to appoint a Special Committee to survey the Situation with reference to the role of the Executive Committee as the American National Committee for the IUGG, and also the general relationships of the Union with its parent body, the National Research Council. In his letter of December 2, 1952, President Bucher appointed those noted above to constitute the Special Committee which included the President, ex officio, as the fifth member. Executive Secretary Waldo Smith was requested to meet with the Committee to assist in gathering the necessary background information and to serve as Secretary. The Committee was authorized to survey the circumstances and report its findings and recommendations to the Executive Committee.

Meetings of the Special Committee were held on January 14, March 10, and April 27, 1953. Individual members of the Committee by common agreement talked with different officials and other persons close to the subject in order to gather representative views. Among those interviewed were Detlev W. Bronk, President of the National Academy, W. W. Rubey, Chairman of the National Research Council, and 15 members of the Section of Geophysics of the National Academy who could be reached for personal interviews during the period. In all, these interviews with officials of the Academy, the Council and members of the Section of Geophysics, numbered 25 or more.

The first meeting, on January 14, was given to thorough review of the circumstances which led to organization of the AGU. The historical developments leading to the present status of the Union were also examined. These items need not be repeated in this report since they will be fully documented in the treatise "On the Organization and Development of the American Geophysical Union" by Jno. A. Fleming which will be published within the next few months [see Transactions, AGU, v. 35, no. 1, pp. 1-46]. In this meeting plans were laid for the individual interviews mentioned in the preceding paragraph. The second and third meetings were devoted to study of the facts and various views and opinions that had been brought together. The Committee concluded that the scientific aims of the AGU and the NRC as regards geophysics would best be served by strengthening the provisions through which the appropriate body or bodies of the AGU would continue to function in close relationship with the NRC to provide (1) the U. S. National Committee for the IUGG, and (2) the geophysical branch of the NRC.

Several forms of organization to accomplish these aims have been proposed, the simplest and most direct being that:

(1) The Executive Committee of the AGU continue to function as the National Committee for the IUGG as now provided in the Preamble to AGU Statutes.

(2) The Committee on Geophysics of the NRC as provided in the Preamble should be reorganized into a new Division of Geophysics of the NRC which would embody the Executive Committee of the AGU and thus in effect continue the AGU functions established in the Preamble. This change might also include provision for (a) the President of AGU to serve ex officio as Chairman of the new Division of Geophysics, subject to certain conditions acceptable to NRC, and (b) the Executive Secretary of AGU to serve as Secretary of the new Division of Geophysics.

It appears that there will be several administrative questions, perhaps some with legal implications which may have to be answered to the satisfaction of the National Research Council. Among these are:

(1) The advantages of a smaller continuing body in the capacity of U. S. National Committee for IUGG to act on current inquiries and plans, and to meet more frequently in preparing a U. S. position. (Several possibilities were discussed by the Special Committee but no conclusions were reached on this point other than the recommendation that the Executive Committee continue as the U. S. National Committee for IUGG.)

(2) Designation of the President and the Executive Secretary of AGU as ex officio Chairman and Secretary respectively of the Division of Geophysics of the NRC might be incompatible with the principle of appointment or election by the NRC of the officers and staff for its own divisions. (Prior approval by NRC of the AGU nominations for officers might meet this objection.)

(3) Legal liability of NRC for acts and decisions of the AGU. Although the AGU organically is still an agency of the NRC, the AGU in fact operates more or less as an independent organization. (This objection might be met by a "save harmless" clause in the agreement.)

(4) AGU manages its own finances. If AGU becomes in effect a new Division of Geophysics in NRC, the Council may wish to have some control over income and disbursements of the AGU.

(5) The NRC is an executive agency for the NAS, and for facility of administration it aims to consolidate subdivisions, rather than to departmentalize them in a form strictly analogous to the sections of the NAS which are designed for a different function.

(6) The housing facilities of the NRC are already crowded and there are no prospects of space to house a new Division of Geophysics embodying the AGU within the office space available to the NRC.

There doubtless are several ways in which these difficulties could be resolved to the mutual satisfaction of the AGU and the NRC if the principal aims are agreed upon. Different views as regards a new Division of Geophysics were brought out in a joint meeting of the Division of Geology and Geography of the NRC with the Sections of Geology and Geophysics of the National Academy on April 28, 1953, attended by members of the Special Committee. At this meeting the Chairman of the NRC Division of Geology and Geography proposed that geophysics be included with geography and geology in a new Division of Earth Sciences, a plan that had been considered a few years earlier. After considerable discussion the joint meeting adjourned with the understanding that further consideration would be given to the two proposals before recommendations were presented to the NRC: (1) consolidation into a Division of Earth Sciences, or (2) a separate Division of Geophysics.

The Special Committee presents the foregoing paragraphs as a summary of the principal factors on which the Executive Committee may wish to base plans for further action. Among the several possible courses of action are: (1) to present the two proposals, above, to the NRC by letter (this step would be contrary, at least in part, to the informal understanding following the joint meeting of the NRC Division of Geology and Geography, the Section of Geology and the Section of Geophysics of National Academy of Sciences on April 28, cited above); (2) to appoint representatives to meet with representatives of NRC to reach agreement with or without specific instructions as to the limits within which such agreement would be acceptable to the AGU; or, (3) to study the general subject further before sending specific recommendations to the NRC.

Under By-Law (5) the membership in this Special Committee terminates automatically on June 30, 1953, and this report is therefore submitted as the Committee's final and only formal report.

SPECIAL ANNOUNCEMENTS

Changes of address--As noted under "Special Announcements" on page 669 of the August, 1953, issue of the Transactions, the Post Office Department has put into effect new regulations pertaining to the return of copies of the Transactions because of wrong address. These copies are either destroyed or, in case of a return such as we are now using on the back cover, are returned to us at parcel-post rates. Thus a copy which costs us less than a cent to send, say, to California is returned to us with postage due of 32 cents. It is therefore urged that all members take prompt steps, even in advance of actual change of address, to let us know this change (1) so that each will get his copy promptly, and (2) AGU will not be put to needless expense in return of undeliverable copies. It is the plan to publish a new Directory of Members either as part of the October or the December issues, and for this reason, too, it is urged that you keep us informed with regard to your proper mailing address.

Tenth General Assembly of the International Union of Geodesy and Geophysics, Rome, Italy, September 14-25, 1954--Note from the heading that there has been a slight change in the dates of this Assembly. The various Association programs are progressing well, and a tentative list of those planning to attend from the United States now totals about 80. If you have plans to go, even though they are tentative, and you have not yet advised the office of AGU, please do so without delay in order that you may be kept informed of developments through releases by the various Associations and the Italian Organizing Committee, and that your name be added to the list of those who are planning to attend. As soon as your plans become definite, one way or the other, you should advise us further. See "Special Announcements" in previous issues of the Transactions and other pertinent information including the need for you to make early reservations for your transportation, and the possibility of chartering a special plane to carry passengers either to Rome or back, or both. We must have about 60 on the chartered plane in order for this to effect economies.

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UNSELFISH
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IN RESEARCH

PROGRAM

THIRTY-FIFTH ANNUAL MEETING

In the Building of the National Research Council - National Academy of Sciences,
the Auditorium of the General Services Building, the Auditorium of the
Department of State, and the National Bureau of Standards
Washington, D. C.

May 3-5, 1954

SCHEDULE OF SESSIONS[a]

Day	Date	Time[b]	Room 1	Room 2	Room 3	Room 4	Room 5
	1954	h m					
Mon.	May 3	09 00	Hydrology	Geodesy	Meteorology	T. M. and E.	. . . . .
		14 00	T. M. and E.	Oceanography	Hydrology	Meteorology	Meteorology
		20 00	Smoker in Ball Room of National Press Club, 14th and F Streets, N. W.				
Tues.	May 4	09 00	Meteorology and Oceanography	Tectonophysics and Volcanology	Hydrology	Meteorology	. . . . .
		14 00[c]	Hydrology and Meteorology	Volcanology	Oceanography	Seismology	. . . . .
		20 00	. . . . .	Evening Session	. . . . .	. . . . .	. . . . .
Wed.	May 5	09 00	Oceanography	Seismology	Meteorology	Volcanology	. . . . .
		13 30	Gen. Assembly	. . . .	. . . . .	. . . . .	. . . . .

[a] For map and key to room numbers, see page 362.

[b] Eastern Daylight Saving Time.

[c] In addition to the sessions shown here, the Section of Terrestrial Magnetism and Electricity will have a joint session with Commission 3 of URSI group at the National Bureau of Standards, Tuesday, May 4, 1954; see T. M. and E. program, page 357.

OFFICERS OF THE UNION

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Maurice Ewing, Vice President
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Waldo E. Smith, Executive Secretary

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Terrestrial Magnetism and Electricity	Victor Vacquier	H. R. Joesting	L. R. Alldredge
Oceanography	Richard H. Fleming	Walter H. Munk	Donald W. Pritchard
Volcanology	William F. Foshag	G. A. Macdonald	Felix Chayes
Hydrology	Harold G. Wilm	Ray K. Linsley	Harry F. Blaney
Tectonophysics	Francis Birch	Louis B. Slichter	James T. Wilson

Program Chairmen

Meteorology: Charles S. Gilman
Volcanology: Ralph S. Cannon, Jr.
Hydrology: Ralph N. Wilson

GENERAL MEETINGS OF THE UNION

SMOKER

Monday, May 3, 1954, 20h 00m to 22h 30m, Ball Room of the National Press Club, 13th Floor, National Press Building, 14th and F Streets, N. W.

This is our usual informal gathering where there is opportunity to renew old acquaintances and make new ones. There will be no program. There is no ticket fee. Refreshments will be available at the regular moderate club prices. These gatherings have been very successful in past years, and a larger room is provided this year to accommodate ever-increasing attendance.

EVENING SESSION

Tuesday, May 4, 1954, 20h 00m, Room 2 (Lecture Room, National Academy of Sciences)

Report
    JOSEPH KAPLAN: Plans for the International Geophysical Year, 1957-1958 (15 minutes)
Lecture
    W. C. KRUMBEIN: Applications of statistics in the Earth Sciences
Sixteenth Award of the William Bowie Medal
    (a) Citation
    (b) Presentation by James B. Macelwane, President
    (c) Response
Social hour with refreshments (in Room 1, Auditorium of the National Academy of Sciences)

GENERAL ASSEMBLY

Wednesday, May 5, 1954, 13h 30m, Room 1 (Auditorium, National Academy of Sciences)

Symposium on Geophysical Models
- (1) FRANK PRESS and JACK E. OLIVER: Model studies of seismic wave propagation
- (2) L. KNOPOFF: Small three-dimensional seismic models
- (3) ROBERT R. LONG: The use of models in geophysical fluid dynamics
- (4) DAVE FULTZ: Time-dependent phenomena in rotating thermal convection
- (5) MAURICE RATTRAY, JR.: Operating characteristics of an oceanographic model of Puget Sound
- (6) W. S. VON ARX: A vorticity model of wind-driven ocean circulation

Business Meeting (Effort will be made to keep this within our usual half hour. Please plan to attend.)
- (1) Reports of officers and special and standing committees, including:
    - (a) General Secretary's report
    - (b) Report of the Committee on Resolutions (E. H. Vestine, Chairman; H. F. Birkenhauer, and Earl Droessler
- (2) Unfinished business
- (3) New business

MEETINGS OF THE SECTIONS

SECTION OF GEODESY

Monday, May 3, 1954, 09h 00m, Room 2 (Lecture Room, National Academy of Sciences)

Business Session

Reports of officers and committees, announcements, and other business

Scientific Session

(1) CARL I. ASLAKSON: Undulations of the geoid in the Bahama Islands
(2) T. J. KUKKAMÄKI: Geodetic distance measurement from the solar eclipse of June 30, 1954
(3) WM. MARKOWITZ: A program for the determination of size and shape of the Earth and other data with the Moon-position camera
(4) C. H. G. OLDHAM: Gravity and magnetic observations along the Alaska highway
(5) EDWARD THIEL: A gravity study of the Keweenawan of northwestern Wisconsin
(6) G. P. WOOLLARD, N. C. HARDING, and J. C. ROSE: The problem of calibrating high-range geodetic-type gravimeters
(7) G. P. WOOLLARD, W. E. BONINI, and J. C. ROSE: Problems in making long-distance and intercontinental gravity connections
(8) W. A. HEISKANAN: Relative significance of the different methods of the modern geodesy
(9) G. D. GARLAND: Results of gravity measurements in North America with the Cambridge pendulum apparatus

SECTION OF SEISMOLOGY

Tuesday, May 4, 1954, 14h 00m, Room 4 (Auditorium, Department of State)

Business Session

Reports of officers and committees, announcements, and other business

Scientific Sessions

(1) RUTLAGE J. BRAZEE: Earthquakes and Earth tides (20 minutes)
(2) Z. FRANKENBERGER: Partition of energy of elastic waves on a boundary of an incompressible solid with possible application for the Earth's core (20 minutes)
(3) JOSEPH J. LYNCH: A seismic recorder for water waves causing two-second microseisms (15 minutes)
(4) DEAN S. CARDER: Transmission of microseisms across the North Atlantic (20 minutes)
(5) WILLIAM L. DONN: On the propagation of microseisms (20 minutes)
(6) CHARLES B. OFFICER: Southwest Pacific crustal structure (20 minutes)

Wednesday, May 5, 1954, 09h 00m, Room 2 (Lecture Room, National Academy of Sciences)

(7) GEORGE V. KELLER: Dispersion of seismic waves near a small explosion (20 minutes)
(8) HOWARD E. TATEL, MERLE A. TUVE, and EVERETT ECKLUND: Studies of reverberation and coherence in wave patterns from seismic shots (20 minutes)
(9) MERLE A. TUVE, HOWARD E. TATEL, and PEMBROKE J. HART: Some limits on seismic wave velocity as a function of depth in the upper 50 kilometers of the Earth's crust (20 minutes)
(10) FRANK NEUMANN: Some new aspects of destructive earthquake motion (15 minutes)
(11) GERALD R. MacCARTHY: An annotated list of earthquakes felt in North Carolina (10 minutes)
(12) JOHN HERSHBERGER: Recent developments in strong-motion analysis (20 minutes)
(13) JOHN HERSHBERGER: A simple strong-motion shaking table (5 minutes)

SECTION OF METEOROLOGY

Monday, May 3, 1954, 09h 00m, Room 3 (Auditorium, General Services Building)

Business Session

Reports of officers and committees, announcements, and other business

Scientific Sessions

Panel Discussion on the Mechanism of Pressure Changes

Moderator: JACOB A. B. BJERKNES; Panel Members: JAMES M. AUSTIN, JULES CHARNEY, GEORGE CRESSMAN, JOE R. FULKS, JEROME NAMIAS, HERBERT RIEHL, ALBERT K. SHOWALTER, and JEROME SPAR

Monday, May 3, 1954, 14h 00m, Room 4 (Auditorium, Department of State)

Symposium on Constant-Level Balloons and Meteorological Trajectories

(1) J. R. SMITH: Some mechanical limitations of data obtained from constant-level balloons (20 minutes)
(2) LESTER MACHTA: Meteorological and balloon trajectories (20 minutes)
(3) MARTIN L. HAAS: The Air Force Moby Dick project (10 minutes)
(4) F. A. BERRY: Constant-level-balloon and meteorological trajectory studies at project AROWA (15 minutes)
(5) F. OHNSORG and HOMER MANTIS: The structure of upper winds as determined by constant altitude balloon
(6) R. R. RAPP: The distribution of the end points of air trajectories (20 minutes)

Monday, May 3, 1954, 14h 00m, Room 5 (Reading Room, National Academy of Sciences)

Panel Discussion on Aviation Weather Services

Moderator: JEROME LEDERER; Panel Members: JEAN DUBUQUE, MAX KARANT, J. C. S. McKILLIP, LESTER SCHROEDER, and JOE TIPPETTS

Tuesday, May 4, 1954, 09h 00m, Room 1 (Auditorium, National Academy of Sciences)

Problems of Oceanographic Meteorology (Jointly with the Section of Oceanography)

(7) CHARLES C. BATES: Report on the recent symposium on interaction of the sea and atmosphere, a resume and an outlook (20 minutes)
(8) WALTER MUNK and E. E. GOSSARD: Waves in the atmosphere of five to ten minute period (20 minutes)
(9) BASIL W. WILSON: Graphical approach to the forecasting of waves in moving fetches (20 minutes)
(10) CHARLES COX and WALTER MUNK: Some problems in optical oceanography (20 minutes)
(11) ALLEN H. SCHOOLEY: Curvature distributions of wind-created water waves (20 minutes)

Tuesday, May 4, 1954, 09h 00m, Room 4 (Auditorium, Department of State)

(12) W. W. KELLOGG: The wind structure and general circulation in the upper atmosphere (30 minutes)
(13) RAYMOND A. MINZER: T-day temperature of the upper atmosphere (20 minutes)
(14) H. RIEHL, F. A. BERRY, and H. MAYNARD: Exploration of the jet stream by aircraft during the winter of 1953 (30 minutes)
(15) W. E. K. MIDDLETON: The color of the overcast sky
(16) ROSS GUNN and PAUL A. ALLEE: A three-thousand cubic meter cloud chamber

Tuesday, May 4, 1954, 14h 00m, Room 1 (Auditorium, National Academy of Sciences)

Panel Discussion of Quantitative Precipitation Forecasting (Jointly with the Section of Hydrology)

Moderator: ALBERT K. SHOWALTER; Panel Members: CHARLES S. GILMAN, DONALD HOUSE, THOMAS F. MALONE, JOSEPH SMAGORINSKY, FRANKLIN F. SNYDER, and RUSSELL J. YOUNKIN

Following brief statements by members of the Panel, the audience will be invited to participate in the discussions.

Wednesday, May 5, 1954, 09h 00m, Room 3 (Auditorium, General Services Building)

Symposium on Dynamic Climatology

(17) H. LANDSBERG: Introductory remarks (5 minutes)
(18) HEINZ H. LETTAU: Dynamical models for the prediction of air and soil temperature response on net radiation cycles (20 minutes)
(19) THOMAS F. MALONE: Some tools and techniques for synoptic climatology (20 minutes)
(20) VANCE A. MYERS: Examples in the application of synoptic climatology to hydrometeorology (20 minutes)
(21) DAVID I. BLUMENSTOCK: Dynamic weather regions - some concepts and examples (20 minutes)
(22) WERNER BAUM: Climatic meteorology: some thoughts on methodology (20 minutes)
(23) WOODROW C. JACOBS: The place of dynamic climatology in the meteorological scheme (20 minutes)

SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY

Monday, May 3, 1954, 09h 00m, Room 4 (Auditorium, Department of State)

Business Session

Reports of officers and committees, announcements, and other business

Scientific Sessions

(1) ELWOOD MAPLE: Sub-audio-frequency oscillations of the geomagnetic field: 0.01 to 1 cps (15 minutes)
(2) W. E. AUSTIN and E. MAPLE: Sub-audio-frequency fluctuations of the Earth's magnetic field at White Oak, Maryland (15 minutes)
(3) JOHN B. WILCOX and ELWOOD MAPLE: Audio-frequency geomagnetic field fluctuations (15 minutes)
(4) EDWIN J. CHERNOSKY: Twenty-seven-day recurrences and non-recurrences in geomagnetic activity (15 minutes)
(5) H. FREEBORN JOHNSTON: List of magnetic observatories and thesaurus of annual values (5 minutes)
(6) H. W. STRALEY, III: Geophysical investigations in the southeastern states (10 minutes)
(7) VICTOR VACQUIER and PAUL R. KINTZINGER: Induced electrolytic polarization in moist clays (15 minutes)

Monday, May 3, 1954, 14h 00m, Room 1 (Auditorium, National Academy of Sciences)

(8) C. W. GARTLEIN: Correlation between K_{CH} and farthest south position of aurora (10 minutes)
(9) H. W. WELLS: F-scatter at Huancayo, Peru, and relation to radio star scintillations (20 minutes)
(10) VICTOR F. HESS and W. D. PARKINSON: The contribution of alpha rays to the ionization balance of the lower atmosphere (15 minutes)
(11) ROSS GUNN: Electric field regeneration in thunderstorms (15 minutes)
(12) SCOTT E. FORBUSH: World-wide changes in cosmic-ray intensity and their relation to magnetic storms and sunspot numbers (20 minutes)
(13) H. K. SEN and M. L. WHITE: Thermal versus gravitational tides in the Earth's atmosphere (20 minutes)

Tuesday, May 4, 1954, 14h 00m (National Bureau of Standards,
Connecticut Avenue at Van Ness Street, N. W.)

The Aurora (Jointly with Commission 3 of the U. S. National Committee of the International Scientific Radio Union)

(14) JOSEPH W. CHAMBERLAIN: The excitation of hydrogen in auroras
(15) J. W. DUNGEY: Theory of geomagnetic micropulsations
(16) VAUGHN AGY: Variations in the probability of occurrence of polar blackouts
(17) C. W. GARTLEIN: The southern side of the overhead auroral zone
(18) A. M. PETERSON and R. L. LEADABRAND: Long-range radio echoes from auroral ionization
(19) K. L. BOWLES: VHF auroral and meteor echoes including simultaneous observations
(20) R. DYCE: 50 Mc/sec auroral echoes obtained at College, Alaska

Note: Commission 3 will hold four additional sessions at the National Bureau of Standards, May 4 and 5, 1954, as shown below.

Wednesday, May 5, 1954, 09h 30m

(1) MARTIN BALSER and A. SILVERMAN: On the statistics of VHF radiation scattered by turbulence
(2) GEORGE R. SUGAR: Some fading characteristics of regular VHF ionospheric propagation
(3) VON R. ESHLEMAN: Theory of radio reflections from electron-ion clouds
(4) JOHN E. JACKSON: Measurements in the E-layer with the Navy Viking rocket
(5) J. CARL SEDDON: Electron densities in the ionosphere
(6) J. SHMOYS and S. KARP: Calculation of charge density distribution of multilayers from virtual thickness data
(7) JOHN M. KELSO: True and group heights in the presence of the Earth's magnetic field

Wednesday, May 5, 1954, 14h 00m

(8) **MARY B. HARRINGTON:** Variations of ionospheric absorption during the past sunspot cycle
(9) **ALLEN M. PETERSON:** Geographical and temporal variations of sporadic E occurrence
(10) **R. A. HELLIWELL:** Height characteristics of sporadic E
(11) **R. DYCE:** VHF auroral and E_s propagation from Cedar Rapids, Iowa, to Ithaca, N. Y.
(12) **M. NICOLET and P. MANGE:** The pole of molecular oxygen in the F region
(13) **F. E. ROACH, A. B. MEINEL, and HELEN PETTIT:** The height of atomic nightglow emissions
(14) **A. B. MEINEL, J. W. CHAMBERLAIN, and C. Y. FAN:** Recent progress in the analysis of the airglow and auroral spectrum

Thursday, May 6, 1954, 09h 30m

(15) **WILLIAM SNYDER:** The polarization of vertical incidence high-frequency echoes at Stanford, California
(16) **M. G. MORGAN:** Progress report on HF polarization measurements at vertical incidence
(17) **R. W. PARKINSON:** Wave solutions, including coupling, for the critical coupling case
(18) **R. L. SCHRAG:** Extended-ranged ionospheric observations at 150 Kc/s
(19) **L. G. ABRAHAM, JR.:** Antenna radiation and plane-wave scattering in the homogeneous non-isotropic ionosphere
(20) **A. T. WATERMAN, JR.:** On the strength of a back-scattered signal
(21) **WILLIAM C. HOFFMAN:** A theoretical model for high-frequency back-scatter from the sea surface via the ionosphere

Thursday, May 6, 1954, 14h 00m

(22) **R. E. LACY and J. J. EGLI:** System study of short-range transmissions via the ionosphere
(23) **J. J. GIBBONS and P. E. BEDIENT:** Some exact solutions of the problem of the relativistic steady-state motion of two electric fluids
(24) **DONALD G. YERG:** The applicability of continuous fluid theory in the higher atmosphere
(25) **DONALD G. YERG:** A six-point correlation method for evaluating winds from amplitude fading records
(26) **R. B. BANERJI:** The autocorrelogram of randomly fading waves, with applications to wind measurements at 150 Kc/s
(27) **W. A. FLOOD:** The fading of ionospheric signals on quiet days
(28) **W. A. FLOOD and K. L. BOWLES:** Interpretation of unusual probability amplitude distributions

SECTION OF OCEANOGRAPHY

Monday, May 3, 1954, 14h 00m, Room 2 (Lecture Room, National Academy of Sciences)

Motion Pictures of Oceanographic Interest

General

(a) Activities of the U. S. Coast and Geodetic Survey; sound; color; 22 minutes
(b) Activities of the International Ice Patrol; sound; color (USCG film)
(c) Ice, men, and ships; sound; color; 15 minutes (USN film)
(d) Cruising northern waters; sound; color; 15 minutes (USN film MN-7439)
(e) Operation Ski-Jump II; sound; color; 22 minutes (USN film MN-7478)
(f) Activities of Chesapeake Bay Institute; sound; black-and-white; 25 minutes

Technical

(g) Ocean tides; silent; black-and-white; 15 minutes; commentary by William E. Maloney, U. S. Navy Hydrographic Office (MacQueen film)
(h) Model studies of ocean currents; silent with titles; color; 25 minutes; (Woods Hole Oceanographic Institution)
(i) Outcrop of the inshore edge of the Gulf Stream as seen from the air; silent with titles; color; five minutes (Woods Hole Oceanographic Institution)
(j) Study of cumulus clouds entering the jet stream; silent with titles; color; five minutes (Woods Hole Oceanographic Institution)
(k) Rough seas viewed from the Caryn and the Atlantis; silent; seven minutes (Woods Hole Oceanographic Institution)
(l) Identification of sea ice; sound; color; 12 minutes (USN film MN-7419-B)
(m) Wave impact on piles; silent with titles; black-and-white; ten minutes, commentary by Rudolph Savage, now of the Beach Erosion Board (Oceanography, Texas A and M College)

Other films may be presented if time and interest permit.

Tuesday, May 4, 1954, 09h 00m, Room 1 (Auditorium, National Academy of Sciences)

Problems of Oceanographic Meteorology (Jointly with the Section of Meteorology; see program and abstracts of Section of Meteorology, papers (7) to (11), pages 356 and 369)

Tuesday, May 4, 1954, 14h 00m, Room 3 (Auditorium, General Services Building)

Business Session
Reports of officers and committees, announcements, and other business
Scientific Sessions

(1) EDWARD L. CORTON, JR.: A study of the Arctic ice pack (20 minutes)
(2) J. R. GERHARDT, K. H. JEHN, and I. KATZ: A comparison of step, pressure, and continuous-wire gage wave recordings in the Golden Gate Channel (15 minutes)
(3) WALTER MUNK, JUNE G. PATTULLO, ROGER R. REVELLE, and ELIZABETH STRONG: The annual change in sea level (20 minutes)
(4) FRANK SNODGRASS and WALTER MUNK: Measurements of long-period waves offshore (15 minutes)
(5) PAUL FERRIS SMITH, JOSEPH D. RICHARD, and FRANK H. STEPHENS: A technique for the special analysis of sound in the ocean (20 minutes)
(6) TSAIHWA J. CHOW and THOMAS G. THOMPSON: Seasonal variation in the concentration of copper in the surface waters of San Juan Channel, Washington

Wednesday, May 5, 1954, 09h 00m, Room 1 (Auditorium, National Academy of Sciences)

(7) JOSEPH BERNSTEIN: The progressive decline in level of the Caspian Sea (15 minutes)
(8) N. P. FOFONOFF: Steady horizontal motion in a frictionless homogeneous ocean (20 minutes)
(9) D. W. PRITCHARD: A study of flushing in a model of the Delaware estuarine system (20 minutes)
(10) KOZO YOSHIDA[a] and HAN-LEE MAO: Upwelling off the California coast (20 minutes)
(11) HAROLD FLINSCH: The effect of deep-water waves on the contours of sand beaches (20 minutes)
(12) ROBERT G. PAQUETTE and CLIFFORD A. BARNES: Some characteristics of currents in deep inshore waters

[a] Denotes speaker.

SECTION OF VOLCANOLOGY

Tuesday, May 4, 1954, about 10h 30m immediately following Scientific Session of the Section of Tectonophysics, Room 2 (Lecture Room, National Academy of Sciences)

(Jointly with the Section of Tectonophysics)

(1) DONALD E. WHITE: Volcanoes, hot springs, and glaciers of Iceland (motion pictures by the author, one hour)

Tuesday, May 4, 1954, 14h 00m, Room 2 (Lecture Room, National Academy of Sciences)

Business Session
Reports of officers and committees, announcements, and other business
Scientific Sessions

(2) FRANCIS R. BOYD: Volcanic history of a portion of the Yellowstone Park rhyolite plateau (14 minutes)
(3) F. CHAYES: Potash feldspar as a by-product of the biotite-chlorite transformation (12 minutes)
(4) GARNISS CURTIS[a], HOWEL WILLIAMS, and WERNER JUHLE (deceased): Evidence against assimilation of andesite by rhyolite in the Valley of 10,000 Smokes, Alaska (14 minutes)
(5) ROBERT W. DUSCHATKO[a] and ARIE POLDERVAART: Spilitic intrusion near Ladron Peak, Socorro County, New Mexico (12 minutes)
(6) E. WM. HEINRICH[a], LEWIS B. KELLUM, and ROBERT LINSLEY: Volcanic rocks of the Sierra de Tlahualilo, Durango, and Coahuila, Mexico (10 minutes)
(7) GEORGE KENNEDY: Causes of explosive eruption of volcanoes (14 minutes)
(8) HOWARD A. POWERS: Some characteristics of basaltic magma in Hawaii (14 minutes)
(9) MATT S. WALTON, JR.: Granite magma and granitization in the emplacement of "granite" (14 minutes)
(10) DONALD E. WHITE: The violent mud volcano eruption of Lake City Hot Springs, Modoc County, California (14 minutes)

Wednesday, May 5, 1954, 09h 00m, Room 4 (Auditorium, Department of State)

(11) N. EFREMOV: Phenomenon of polar isomorphism in terms of lattice energies (10 minutes)
(12) L. F. HERZOG[a], W. H. PINSON, and P. M. HURLEY: Isotopic variations in strontium; I, Preliminary survey (14 minutes)
(13) WILLIAM H. PINSON, JR.: Trace-element composition of a carbonaceous chondrite (14 minutes)
(14) H. A. SLACK and W. C. KRUMBEIN[a]: Measurement and statistical evaluation of low-level radioactivity in rocks (14 minutes)
(15) ROBERT J. UFFEN: A method of estimating the thermal conductivity of the Earth's mantle (10 minutes)
(16) G. J. WASSERBURG[a] and R. J. HAYDEN: A^{40}-K^{40} age determinations (14 minutes)
(17) ROBERT BALK: Kimberlitic plugs in northeastern Arizona (14 minutes)
(18) DAVID SCHULZ: A study of thermal convection and its possible relation to the circulation of fluids in the Earth (10 minutes)

[a] Denotes speaker.

SECTION OF HYDROLOGY

Monday, May 3, 1954, 09h 00m, Room 1 (Auditorium, National Academy of Sciences)

Business Sessions
- (a) Report of officers
- (b) Other business

Scientific Sessions
(R1) R. D. MILLER: Report of the Research Committee on Physics of Soil Moisture (10 minutes)
(1) G. E. MANGER[a], G. L. GATES, and R. A. CADIGAN: Progress report: Original-state core studies (20 minutes)
(R2) J. C. FRYE: Report of the Research Committee on Ground Water (10 minutes)
(2) MAHDI S. HANTUSH and C. E. JACOB[a]: Flow to an eccentric well in a leaky circular aquifer (20 minutes)
(3) H. A. WAITE and H. E. THOMAS: Effect of the current drought upon water supplies in Cedar City Valley, Utah (20 minutes)
(4) DAVID K. TODD: Unsteady flow in porous media by means of a Hele-Shaw viscous fluid model (25 minutes)
(5) BORIS J. BERMES[a] and C. E. JACOB: Further correlation of precipitation and groundwater levels on Long Island, New York (20 minutes)
(6) R. L. CUSHMAN and L. C. HALPENNY: Effect of the western drought on the water resources of Safford Valley, Arizona, 1940-52 (20 minutes)

Monday, May 3, 1954, 14h 00m, Room 3 (Auditorium, General Services Building)

(R3) LEONARD SCHIFF: Report of the Research Committee on Infiltration (10 minutes)
(R4) M. D. HOOVER: Report of the Research Committee on Evaporation and Transpiration (10 minutes)
(7) GEORGE S. BENTON[a] and JACK DOMINITZ: The use of atmospheric data in the evaluation of evapotranspiration (25 minutes)
(R5) L. D. DONEEN: Report of the Research Committee on Chemistry of Natural Waters (10 minutes)
(R6) R. A. WORK: Report of the Research Committee on Snow (10 minutes)
(R7) ARTHUR JOHNSON: Report on the Research Committee on Glaciers (10 minutes)
(8) LAWRENCE E. NIELSEN: Regimen and movement of the Taku Glacier, Alaska (20 minutes)
(9) D. B. KRINSLEY: Glaciomarine chronology in the Thule area, Greenland (20 minutes)
(10) ERNEST H. MULLER[a] and HENRY W. COULTER: Observations on the Knife Creek Glaciers, Katmai National Monument, Alaska (20 minutes)
(R8) E. F. BRATER: Report of the Research Committee on Lakes (10 minutes)
(R9) D. C. BONDURANT: Report of the Research Committee on Dynamics of Streams (10 minutes)

Tuesday, May 4, 1954, 09h 00m, Room 3 (Auditorium, General Services Building)

(R10) W. E. HIATT: Report of the Research Committee on Precipitation (10 minutes)
(11) W. T. WILSON: Analysis of winter precipitation observations in the Cooperative Snow Investigations (15 minutes)

(12) **FRANK C. ALLEN, ROBERT E. GLOVER, WALTER U. GARSTKA, and HOWARD M. POSZ:** Heated precipitation-gage intake tube (10 minutes)
(R11) **W. D. POTTER:** Report of the Research Committee on Runoff (10 minutes)
(13) **L. D. LOVE:** The effect of the killing of spruce and pine by bark beetles on the streamflow of White River, Colorado (25 minutes)
(14) **H. E. BROWN and E. G. DUNFORD:** Streamflow in relation to extent of snow cover (20 minutes)
(R12) **L. C. GOTTSCHALK:** Report of the Research Committee on Land Erosion (10 minutes)
(15) **RONALD L. IVES:** Past and present courses of the Sonoyta River (20 minutes)
(16) **E. G. DUNFORD:** Surface runoff and erosion as affected by precipitation characteristics and land use in the Colorado Front Range (25 minutes)
(17) **ELLIOTT M. FLAXMAN and ROBERT L. HOBBA:** Some factors affecting rates of sedimentation in the Columbia River basin (to be presented by Louis C. Gottschalk) (25 minutes)
(18) **B. A. BAKHMETEFF** (deceased) and **N. V. FEODOROFF**[a]: The outflow through slits (20 minutes)

Tuesday, May 4, 1954, 14h 00m, Room 1 (Auditorium, National Academy of Sciences)

Panel Discussion on Quantitative Precipitation Forecasting, Present and Future (Jointly with the Section of Meteorology; see program of the Section of Meteorology, page 356)

[a] Denotes speaker.

SECTION OF TECTONOPHYSICS

Tuesday, May 4, 1954, 09h 00m, Room 2 (Lecture Room, National Academy of Sciences)

Business Session
  Reports of officers and committees, announcements, and other business
Scientific Sessions
(1) **JOHN W. HARRINGTON:** Are differences in crustal layering a logical basis for the analysis of orogeny?
(2) **JOHN S. SUMNER:** Consequences of a polymorphic transition at the Mohorovicic discontinuity
(3) **WILLIAM B. FARRINGTON:** Analysis of stress conditions in the upper Spraberry in western Texas
(4) **J. TUZO WILSON:** A physical explanation of graben and zwischengebirge

(Upon completion of this program, the session will become a joint one with the Section of Volcanology; see program of the Section of Volcanology, paper (1), page 359)

NOTES

Room Reservations--Make hotel or room reservations directly with the hotel of your choice as soon as possible (see December 1953 issue, p. 974, for word concerning hotels at which block bookings have been made). Bear in mind that advance bookings on which deposits have not been made are cancelled two weeks in advance, and thus, during this interval, chances of making a reservation may be quite good. Even though no advance reservation has been made, it is possible to arrange for quarters after arrival in Washington through the Housing Committee of the Washington Board of Trade (1616 K Street, N. W., Washington 6, D. C., telephone REpublic 7-2600); but they may find it necessary to direct you to a tourist home.

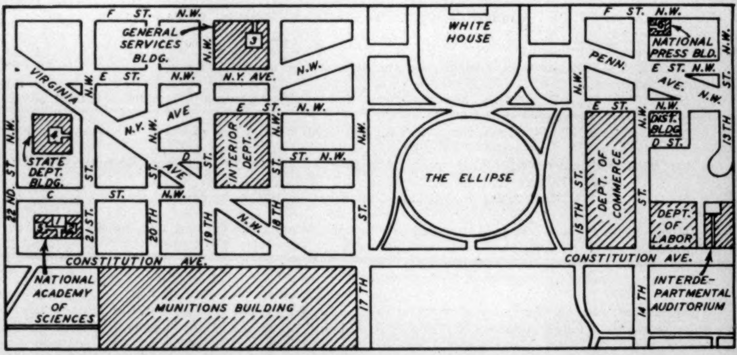
NAS Symposium on the International Geophysical Year--On April 28, 1954, at 14h 00m at the National Academy of Sciences in connection with its spring meeting, there will be a Symposium on Some Scientific Aspects of the International Geophysical Year. Nine papers will be given as follows: Sydney Chapman (President of the International Union of Geodesy and Geophysics and President of the Special Committees of the International Council of Scientific Unions on the International Geophysical Year), Introduction: Joseph Kaplan (Chairman of the IGY Committee from the United States), The Scientific Program of the International Geophysical Year; H. G. Booker, Morphology of Ionospheric Storms; A. B. Meinel, Morphology of the Aurora; F. E. Roach, Diurnal and Seasonal Changes of Air-Glow; Harry Wexler, Transport Problems in the Atmosphere; F. L. Whipple, The Evidence for Winds in the Outer Atmosphere; D. H. Menzel, Solar Activity and Terrestrial Disturbance; and L. M. Gould, Geographic Basis for Antarctic Scientific Observation.

Spring Meeting of URSI--The Spring Meeting of the USA National Committee of the International Scientific Radio Union will be held at the National Bureau of Standards in Washington, D. C., May 4-6, 1954. All of the seven Commissions are arranging programs. The session of Commission 3 (Ionospheric Radio Propagation) relating to the Aurora will be held jointly by the Section of Terrestrial Magnetism and Electricity and the Commission, as shown in the program of the Section. Other details of the program may be secured from William E. Gordon (Secretary of the USA National Committee, URSI), School of Electrical Engineering, Cornell University, Ithaca, N. Y.

Meeting of the American Meteorological Society--The American Meteorological Society will hold its Spring Meeting at the Lord Baltimore Hotel in Baltimore, April 28-30, 1954. In connection with this meeting, the joint AGU-AMS Committee on the Interaction of the Sea and the Atmosphere has arranged a full day's program for April 30 covering the theory of the flux of heat, momentum, water, and salt, the climatic and forecasting aspects, and the outlook for the future. For more details, write to the Chairman of the Committee, Charles C. Bates, 7810 Gateway Boulevard, S. E., Washington 28, D. C.

Registration--All members and guests attending any session are requested to complete cards of registration at the Main Registration Desk at the entrance to the Building of the National Research Council - National Academy of Sciences, where Receptionists will be available to supply information regarding meetings, membership, telephone and mailing facilities, and other local matters. An auxiliary Registration Desk will also be maintained at the entrance to Room 3 (Auditorium, General Services Building) and Room 4 (Auditorium, Department of State). There is no charge for registration.

Map showing locations of meeting rooms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CONSTITUTION AVE.
CONSTITUTION AVE.
NATIONAL ACADEMY OF SCIENCES
MUNITIONS BUILDING
17TH
14TH
INTERDEPARTMENTAL AUDITORIUM

1--Auditorium, National Academy of Sciences - National Research Council Building
2--Lecture Room, National Academy of Sciences - National Research Council Building
3--Auditorium, General Services (Old Interior) Building
4--Auditorium, Department of State
5--Reading Room, National Academy of Sciences - National Research Council Building

Discussion--Within the available time, opportunity will be given for discussion from the floor following the oral presentation of a paper. Discussants are urged to prepare their comments for consideration for publication with the paper.

Resolutions--Chairman E. H. Vestine (phone WOodley 6-0863) of the Union's Committee on Resolutions, desires to have this Committee fully advised by 15h 00m, Tuesday, May 4, 1954, of any resolutions to be submitted in order that this Committee may have opportunity to prepare them in final form for presentation at the Business Session of the Union on Wednesday afternoon, May 5, 1954. Each resolution presented to the Committee should include (a) names of original submitters, (b) whether presented to a Section, and action taken, and (c) whether action is desired in the Business Session or whether the resolution is to be regarded as being only for a particular Section or as one to be more effective as a general resolution of the whole Union. In addition to the Union's Committee on Resolutions, each Section has a Resolutions Committee. Section officers can supply information concerning these.

Conference Room--The Reading Room (west end of the first floor behind the Library) of the National Academy of Sciences is available by arrangement, except as formally scheduled for meetings, for conferences. See John N. Adkins, Chairman of the Committee on Meetings, for assignment.

Lounge--The Board Room (behind the Lecture Room), the Library (opposite the Lecture Room), and the Reading Room (behind the Library) (when not in use for meetings, conferences, and committee meetings) of the National Academy of Sciences are available for the use of members to meet friends and to hold informal conferences. Those held in the Library should pay deference to the usual library regulations with regard to quietude.

Standard of Time--The District of Columbia will be on Eastern Daylight Saving Time at the time of the meeting.

ABSTRACTS OF PROGRAM PAPERS

EVENING SESSION

W. C. Krumbein (Northwestern University, Evanston, Ill.) Applications of Statistics in the Earth Sciences--Many Earth phenomena involve simultaneous change of several variables, usually not directly under man's control. Isolation of certain phenomena permits controlled laboratory experimentation, but there is also need for study of simultaneous natural variation in several factors, which in this context supplements rather than competes with laboratory experimentation. Statistical design provides a technique adapted to both laboratory experimentation and the observation of the effects of natural variations. The present paper reviews the application of some statistical principles to the Earth sciences, with special reference to the design of experiments for analysis of variance. Several general problems are considered, including the nature of distributions encountered in Earth science data, their transformations for analysis of variance, sampling design, and estimation of error. Geological examples are used, but parallels are drawn from other Earth science fields. The use of probabilistic models in developing Earth process theories is touched upon briefly.

SYMPOSIUM ON GEOPHYSICAL MODELS

(1) Frank Press and Jack E. Oliver (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) Model Studies of Seismic Wave Propagation--Propagation of Love and Rayleigh waves in many types of layered media is investigated. Effects of sphericity of the Earth, coupling to atmosphere or hydrosphere, complicated layering, and influence of the Earth's core are investigated. Behavior of surface waves at various discontinuities in the transmitting layers is studied. Some data have been gathered on effects of imperfect elasticity of the transmitting medium.

(2) L. Knopoff (Institute of Geophysics, University of California, Los Angeles, Calif.) Small Three-Dimensional Seismic Models--Studies during the last four years in the development of small three-dimensional models are reported. In this work the excitation has usually been a simple pulse of about five microseconds duration. Small crystal sources and receivers of about six mm maximum dimension are used. Coupled electrical pulse shaping and mechanical feedback is employed to produce a simple reproducible elastic pulse at the "shot point", and to obtain suitable response characteristics at the receiver. The simple models thus far used are usually less than 60 mm in maximum dimension, and the compressional waves are of wave-length between a half and two cm in the various materials used. Results for refraction and reflection techniques are shown, including reflections from boundaries of several types, involving both slight and gross discontinuities. The influence of boundary conditions on the wave forms of reflections is of special interest. In the case of wax, the influence of imperfections of elasticity are notably exhibited. Here the results accord with theoretical predictions based on a viscoelasticity of a simple type.

(3) Robert R. Long (Johns Hopkins University, Baltimore, Md.) The Use of Models in Geophysical Fluid Dynamics--Present knowledge of the behavior of fluid systems in which the motion can not be assumed irrotational is limited to "perturbation solutions" of the linearized equations of motion. Such systems are of great importance in geophysical problems because of the presence of density gradients and rotation. Some preliminary experimental work along these lines indicates that perturbation solutions may have very limited application to problems of this type, and that

finite disturbances of stratified and rotating fluids lead to important phenomena that are not contained in the approximate solutions. In particular the very existence of assumed steady-states is questionable in many cases; in others, shock waves are a prominent feature.

(4) Dave Fultz (University of Chicago, Chicago, Ill.) Time-Dependent Phenomena in Rotating Thermal Convection--Along with general remarks on the regimes of motion which so far appear to be distinguishable in certain cases of rotating thermal convection, two examples of simple wave and cellular motions showing special time dependences are discussed. Connections with the meteorological phenomena of the index cycle, blocking, etc., and with quasi-geostrophic adjustments are pointed out. A short motion picture is included.

(5) Maurice Rattray, Jr. (University of Washington, Seattle, Wash.) Operating Characteristics of an Oceanographic Model of Puget Sound--The model, constructed to a horizontal scale of 1/40,000 and vertical of 1/1152, is equipped with a tide-producing mechanism and means for adding regulated amounts of fresh and salt water. Tests made include the following: the response of the water level to individual tidal constituents, and to typical tides; current patterns throughout tidal periods; density structure under equilibrium conditions and that subsequent to controlled changes in source water. The behavior of the model agrees well with the prototype.

(6) W. S. von Arx (Woods Hole Oceanographic Institution, Woods Hole, Mass.) A Vorticity Model of the Wind-Driven Ocean Circulation--Experiments begun in 1951 show that it is possible to produce a satisfactory replica of the climatological mean circulations of the northern hemisphere oceans by applying suitable wind stresses to homogeneous water in a rotating model. The scaling of this model is based on a vorticity criterion which will be discussed together with photographs of the experimental results.

SECTION OF GEODESY

(1) Carl I. Aslakson (U. S. Coast and Geodetic Survey, Washington 25, D. C.) Undulations of the Geoid in the Bahama Islands--There are certain requirements for knowing the relative locations of the geoidal undulations, the absolute values of the highs and lows being of minor importance. A paper in 1953 described a method of computing these undulations from observations of the deflection of the vertical by using condition equations. This paper describes a similar computation, utilizing observation equations, assuming a linear change of the deflection between observation points.

(2) T. J. Kukkamäki (The Mapping and Charting Research Laboratory, Ohio State University, Columbus, Ohio) Geodetic Distance Measurement from the Solar Eclipse of June 30, 1954--The Air Force Cambridge Research Center has established two research projects to use the solar eclipse of June 30, 1954, for the geodetic distance measurements. One project has been given to the Ohio State University, which will send four expeditions to photograph directly the change of the size of the Sun's crescent as well as the change of the flash spectrum. The other project, given to Georgetown University, will send fifteen expeditions which will record the change of the total light intensity of the Sun during the eclipse by aid of a photoelectric cell. The arrangements of the work of these expeditions and the significance of the expected result of these expeditions when connected with the observations of the similar Finnish and Swedish expeditions is discussed.

(3) Wm. Markowitz (U. S. Naval Observatory, Washington 25, D. C.) A Program for the Determination of Size and Shape of the Earth and Other Data with the Moon-Position Camera--The position of the Moon may be accurately determined whenever it is clearly visible with the dual-rate camera, which simultaneously tracks the Moon and stars. The camera has been in use since June, 1952, at the U. S. Naval Observatory for the purpose of determining uniform time, free from irregularities in the rate of rotation of the Earth. A world-wide photographic Moon program of geodetic interest is planned for the International Geophysical Year, 1957-58. Observations will be made at about 20 observatories and the plates will be measured at four of these.

The distance from the Earth to the Moon will be determined by pairs of stations, several thousand kilometers apart, whose separation has been obtained by triangulation. It will then be possible to determine the three geocentric coordinates of each station, with probable errors of the order of 40 m. The Moon program will give, independent of previous determinations, new determinations of: (a) The size and shape of the Earth; (b) possible departure from the spheroidal form; (c) geodetic latitudes and longitudes; and (d) a World Geodetic System.

(4) C. H. G. Oldham (Department of Physics, University of Toronto, Toronto, Ontario, Canada) Gravity and Magnetic Observations along the Alaska Highway--Gravity and magnetic readings have been made at about five-mile intervals along the Canadian section of the Alaska Highway. The

gravity observations were extended with a station spacing of about 20 miles to Fairbanks, Alaska. Profiles of the Bouguer gravity anomalies, and the vertical magnetic intensity have been plotted, and their major features interpreted. A negative Bouguer anomaly of 70 mgal is observed over the northern end of the Rocky Mountains. An undulation at the base of the crust, with a maximum amplitude of 16,000 ft is sufficient to explain this anomaly. Low-density granitic rocks are more probably the cause of an anomaly of similar magnitude, observed over the Cassiar Mountains. The field work was carried out during the summer of 1953 whilst the writer was employed by the Dominion Observatory. The interpretation is to be included as part of a Ph.D. thesis at Toronto.

(5) Edward Thiel (Department of Geology, University of Wisconsin, Madison 6, Wisc.) A Gravity Study of the Keweenawan of Northwestern Wisconsin--Traverses leading from Madison to the West Coast and Alaska have detected an intermittent belt of positive Bouguer anomalies extending from the Canadian border southward into Kansas. Reconnaissance coverage is now complete for the part of the anomalous area in northwestern Wisconsin and adjacent Minnesota. Positive anomalies occur here over basic Keweenawan extrusives, attaining a maximum value of +56 mgal. Over the adjacent River Falls and Lake Superior synclines the anomaly decreases to -88 and -92 mgal respectively. The greatest deficiency of gravity associated with the Lake Superior syncline is centered over the Bayfield Penninsula. Seven traverses with a station interval of 0.5 mile cross the cyncline and the lavas perpendicular to the strike. The major faults are clearly indicated. Where the traverses cross the Gogebic Range the station interval is reduced to 0.1 mile. Here the Ironwood iron formation appears as a three-milligal high, and a wedge of conglomerate between lava as a low. Seismic refraction work gives drift thicknesses and basement rock velocities on the Gogebic Range. Rock densities and principal facts for key gravity stations are given in appendices.

(6) G. P. Woollard, N. C. Harding, and J. C. Rose (University of Wisconsin, Madison 6, Wisc.) The Problem of Calibrating High-Range Geodetic-Type Gravimeters--Various methods of calibration that have been adopted for the calibration of gravimeters are considered and discussed in terms of the potential and actual accuracy of calibration obtained. Comparative data are given as obtained with different types of gravimeters calibrated by the same method and for the same type of gravimeter as calibrated by different methods. The uncertainties in calibration are shown to be the major factor determining differences in gravimeter values reported by different investigators.

(7) G. P. Woollard, W. E. Bonini, and J. C. Rose (University of Wisconsin, Madison 6, Wisc.) Problems in Making Long-Distance and Inter-continental Gravity Connections--The problems associated with making gravity connections over large distances are reviewed and discussed. Comparative data are presented as obtained using various types of pendulum equipment and gravimeters. Discrepencies in results are discussed in terms of their probable source.

(8) W. A. Heiskanen (Ohio State University, Columbus, Ohio, and Finnish Geodetic Institute and International Isostatic Institute, Helsinki, Finland) Relative Significance of the Different Methods of the Modern Geodesy--In geodesy, some ancient and many new methods will be applied for solving the crucial problems of geodesy: determination of the dimensions of the reference ellipsoid, and the shape of the geoid as well as the computation of the geodetic control points. Therefore, the possibilities, limitations, and relative significance of the different methods used or planned to be used in geodesy such as the classic triangulation, flare triangulation, and rocket-star triangulation, arc-measuring method, Shoran and related methods, the solar eclipse, occultation and Moon photographing (Markowitz) methods as well as the gravimetric method will be discussed.

(9) G. D. Garland (Dominion Observatory, Ottawa, Ontario, Canada) Results of Gravity Measurements in North America with the Cambridge Pendulum Apparatus--The two-year program of observations by the Dominion Observatory with pendulums on loan from Cambridge University, England, has been completed. This paper presents a summary of the results which have been obtained, and an estimate of the reliability of these observations. One phase of the work has been the connection of Ottawa to Teddington, England, and to Washington, so that a new adjustment of the North American national gravity stations relative to Europe is possible. The second project discussed is the establishment of a line of stations, suitable for calibration purposes, between Mexico City and Fairbanks, Alaska.

SECTION OF SEISMOLOGY

(1) Rutlage J. Brazee (U. S. Coast and Geodetic Survey, Washington 25, D. C.) Earthquakes and Earth Tides--The tidal stress for several hours preceding and following each of 300 earthquakes is analyzed for possible trigger effects. Analysis is made with respect to (1) distribution of quakes on the vertical tidal spectrum; and (2) horizontal azimuth and magnitude of stress at the time of each quake.

(2) Z. Frankenberger (Gulf Research and Development Company, Pittsburgh, Pa.) Partition of Energy of Elastic Waves on a Boundary of an Incompressible Solid with Possible Application for the Earth's Core--An attempt has been made to interpret K-waves as transverse body waves. As a consequence, the Earth's core is considered as an almost incompressible solid. For easier computation, the velocity of longitudinal waves in the core is supposed to approach infinity. Partition of amplitudes and energies is then derived from Zoeppritz's equations. Correlation of computed values with measured quantities is open for discussion.

(3) Joseph J. Lynch (Fordham University, New York 58, N. Y.) A Seismic Recorder for Water Waves Causing Two-Second Microseisms--To investigate the mechanism of the origin of microseisms in a body of water, an instrument has been designed to record water vibrations simultaneously with ground vibrations on shore.

(4) Dean S. Carder (U. S. Coast and Geodetic Survey, Washington 25, D. C.) Transmission of Microseisms across the North Atlantic--A comparison of microseisms recorded at Bermuda and North American stations indicates that the North Atlantic between the continent and Bermuda has a relatively high absorption rate for microseisms having periods of seven seconds or less. If the source area is on the margin of the continent and the period on the continent is 6.5 to seven seconds, energy absorption over a 1000-km oceanic path is probably at least an order greater than over an equal continental path. If the period on the continent is nine seconds, the relative absorption over the oceanic path is much less than this and the oceanic passage is accompanied by a slight increase in period. All four- to five-second microseisms recognizable on the Bermuda Milne-Shaw records are believed to have local sources.

(5) William L. Donn (Brooklyn College, Brooklyn, N. Y., and Lamont Geological Observatory, Palisades, N. Y.) On the Propagation of Microseisms--Studies of microseism propagation have been made for many different sources and for widely separated stations distributed along the Atlantic and Gulf coasts of the United States and the West Indies and across the continent to the Alaskan coast. A summary of the results indicates: (1) microseisms of long period, eight to ten seconds, propagate across the continent with surprisingly little attenuation and change of period and permit relatively reliable directional determinations; (2) considerably greater attenuation occurs for microseisms that have paths across parts of the Atlantic Ocean; (3) many stations on the eastern and Gulf coasts and possibly the West Indies show simultaneous microseism excitation when intense storms approach or travel across the continental edge; and (4) many problems involving microseisms appear to be explainable on the basis of differential propagation.

(6) Charles B. Officer (Woods Hole Oceanographic Institution, Woods Hole, Mass.) Southwest Pacific Crustal Structure--This investigation has been concerned with the determination of the crustal thicknesses of the various features of the Southwest Pacific from Love and Rayleigh wave dispersion characteristics. The crustal thickness of the Tasman Basin between New Zealand and Australia is the same, five to ten km, as that for the South Pacific Basin to the east of New Zealand. The thickness of East Cape - Kermadec - Tonga Ridge bordering the South Pacific Basin on the west and that of the Lord Howe Rise bordering the Tasman on the northeast is 20-25 km. A crustal refraction profile over New Zealand gives a thickness of 20 km. The interior region of ridges and troughs, northeast of New Zealand, has an average thickness of 15-20 km. The results are indicative of an origin from successive orogenic belts built out over an oceanic crust. The area is not part of an extensive continent.

(7) George V. Keller (U. S. Geological Survey, Washington 25, D. C.) Dispersion of Seismic Waves near a Small Explosion--The characteristics of the ground vibrations caused by the detonation of small dynamite charges were studied at distances from 10 to 3070 feet from the point of detonation. The motion which was observed could be separated into several types on the basis of velocity and particle motion paths. The major part of the recorded motion following the arrival of body waves exhibited strong dispersion. A comparison of this dispersion with that theoretically predicted for Rayleigh waves by Love, Sezawa, and others, showed that these motions are probably Rayleigh waves of the first and second types. The complex particle motion orbits observed near the shot point are probably a result of the overlap of these two normal modes of surface wave propagation. This paper is the adaptation of a doctorate dissertation, Division of Geophysics and Geochemistry, Pennsylvania State University.

(8) Howard E. Tatel, Merle A. Tuve, and Everett Ecklund (Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.) Studies of Reverberation and Coherence in Wave Patterns from Seismic Shots--"Signal to noise ratio" is almost a useless concept in seismic work because the ground continues to vibrate strongly and continuously after the compressional wave (P) from a shot (or quake) has passed by and when no slower waves (S or R or L)

from the disturbance can yet have directly reached the observing point. Hypotheses involving single or multiple scattering have proved unsatisfactory and even untenable, because the continued ground motion or "reverberation" often shows quasi-coherence over an area of several wavelengths. We have been led to the view that the reverberation, the quasi-coherence, the "preservation of initial pattern," and the marked relation of the records to the vicinity of the receiver (not the shot) can all be explained if the reverberation is primarily a matter of conversion of the body (P) waves into surface waves (chiefly Rayleigh) near the receiver. These surface waves die out slowly because they are trapped in the surface. Experiments to test this hypothesis using a special arrangement of two strain seismometers and one vertical velocity instrument for identification of Rayleigh (conversion) waves will be described, along with other related material.

(9) Merle A. Tuve, Howard E. Tatel, and Pembroke J. Hart (Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.) Some Limits on Seismic Wave Velocity as a Function of Depth in the Upper 50 Kilometers of the Earth's Crust--A detailed study of the Chesapeake Bay region has been made, utilizing many records on large explosive shots. Travel-time curves, amplitudes, and numerous "phases" after the first arrival have been carefully studied. Only one conspicuous phase appears repeatable and consistent; this is considered to be a reflection from a discontinuity at depth (Mohorovicic) or a refraction from a transition region of roughly similar depth (30 km or so). Other studies, also utilizing hundreds of stations, have been made in Minnesota, near Puget Sound, and elsewhere. Various hypothetical constructions of velocity as a function of depth, involving a variety of layers and other simple ideas, can be ruled out by the observations. Transitions of small velocity contrast at depths beyond 15 or 20 km might be conjectured, but necessarily will escape observation by seismic or earthquake procedures.

Simple illustrations will be given of typical velocity-depth curves in two groups, those which are consistent with our observations and samples of others which are not consistent. There is a modest increase in velocity with depth, but most of the change from 6 to 8 km/sec is concentrated in a restricted depth range, at or near the "Moho." No evidence for "intermediate layers" has been found.

(10) Frank Neumann (University of Washington, Seattle, Wash.) Some New Aspects of Destructive Earthquake Motion--Using descriptive reports on earthquake effects and strong-motion seismograph data relationships are established between (1) the various grades of the Modified Mercalli Intensity Scale of 1931, (2) epicentral distance, and (3) the period and acceleration of instrumentally recorded ground waves. A provisional quantitative earthquake intensity scale is developed which covers the period as well as the acceleration factors. Modification is required for increasing epicentral distance. Simple formulas are developed for the distribution of intensity on major types of basement rock making it possible to assign an intensity anomaly to any site with reference to the intensity in the underlying basement rock. Instrumental data indicate that shock wave vibrations in basement rock possess definite period-acceleration distribution characteristics depending on the physical characteristics of the rock. A period-acceleration envelope developed from a given record is shown to be a measure of the intensity at the instrument site and, under certain circumstances, also a measure of intensity in the underlying basement rock. Application of the new findings to the study of earthquakes in the State of Washington is discussed.

(11) Gerald R. MacCarthy (University of North Carolina, Chapel Hill, N. C.) An Annotated List of Earthquakes Felt in North Carolina--In connection with recent establishment of a seismological station at the University of North Carolina in Chapel Hill, an annotated list of North Carolina earthquakes is being compiled, chiefly from contemporary newspaper accounts. So far about 64 earthquakes have been so listed, of which 35 or about 55 pct have had epicenters within, or on the borders of, North Carolina. The earliest one so far noted was the New Madrid earthquake of 1811, and the most recent one the eastern Tennessee shock of January 1, 1954. Virginia is distinctly more active seismically than is North Carolina, while, aside from the shocks originating in the Charleston area, South and North Carolina are on almost equal footing. Thus the 1947 edition of the Earthquake History of the United States credits North Carolina with nine earthquakes, of which three are classed as important. Virginia is credited with 16 shocks, of which six were important. South Carolina is credited with some nine shocks, of which five were felt over more than 20,000 sq mi. Three of these were from the Charleston epicenter. Omitting them, South Carolina and North Carolina are approximately equal in respect to seismic activity.

(12) John Hershberger (U. S. Coast and Geodetic Survey, Washington 25, D. C.) Recent Developments in Strong-Motion Analysis--The integration of acceleration records as performed by the U. S. Coast and Geodetic Survey to produce velocity and displacement curves, has nearly always required the use of arbitrary "adjustments," in addition to the three legitimate adjustments involved

in fixing the two constants of integration and the acceleration axis. These additional adjustments were justified on the assumption of accelerometer zero-shifts. An improved accelerometer eliminated the possibility of zero-shifts, thereby preventing the continued use of the former adjustments. Since then acceptable integration results have not been obtainable, except only for short periods of ground motion. The Carder displacement meter has thoroughly proved its superiority over integration as a means for obtaining displacement information of general engineering significance, and is being increasingly used for this purpose.

(13) John Hershberger (U. S. Coast and Geodetic Survey, Washington 25, D. C.) A Simple Strong-Motion Shaking Table--Recently the U. S. Coast and Geodetic Survey built a very inexpensive strong-motion shaking table with no driving mechanism except a lever to be operated by hand. Details of the table, and some of the results obtained, are shown.

SECTION OF METEOROLOGY

(1) J. R. Smith (General Mills, Inc., Minneapolis 13, Minn.) Some Mechanical Limitations of Data Obtained from Constant-Level Balloons--The role of constant-level balloons in scientific experimentation is reviewed. General principles of operation are discussed, with emphasis on operational problems which limit the value of data obtained. Various types of meteorological data which may be obtained are enumerated.

(2) Lester Machta (U. S. Weather Bureau, Washington 25, D. C.) Meteorological and Balloon Trajectories--Three methods of constructing meteorological trajectories are reviewed in the light of their present and future potential. These methods are identified as the air-mass tracer, the dynamical, and the kinematic methods. A program whereby the large-scale features of balloon trajectories may improve the understanding of the dynamics of the atmosphere is suggested. The constant-pressure balloon trajectory may offer the first successful means for studying ageostrophic wind components and quasi-horizontal accelerations without resorting to statistical treatments.

(3) Martin L. Haas (Air Force Cambridge Research Center, Cambridge 39, Mass.) The Air Force Moby Dick Project--A brief description of the "Moby Dick" tracking facilities, data-collecting methods, instrumentation, etc. A short discussion is given on the accuracy of the balloon position data and the least mean square computations used in determining the balloon's position.

(4) F. A. Berry (U. S. Fleet Weather Central, Norfolk, Va.) Constant-Level-Balloon and Meteorological Trajectory Studies at Project AROWA--Interest in constant-level-balloons and meteorological trajectories has been concentrated in three major portions of the Applied Meteorological Research Program at Project AROWA. The primary effort has been directed toward the development of a differential analyzer capable of producing trajectory solutions to pressure contour configurations found on actual upper-air charts, and the utility of such solutions as a means of predicting the trajectories of air particles and of balloons through various pressure configurations, as well as predicting changes in the patterns themselves. Continuance of these investigations will be coupled with the development of constant level balloons as a vehicle for transosonde systems. In connection with tropical research, development and testing of low-level plastic balloons capable of being launched from aircraft in flight and tracked by airborne radar was conducted. The progress attained on each of these phases and the anticipated investigations are outlined.

(5) F. Ohnsorg and H. T. Mantis (University of Minnesota, Minneapolis, Minn.) The Structure of Upper Winds as Determined by Constant-Altitude Balloons--The power spectrum of the velocities measured on four constant-altitude balloon flights are presented and discussed. In all but one case the higher powers of long-period or large-scale motion were separated from the turbulence region (frequencies higher than those investigated) by a region of low power. In one case, which appeared to be associated with convection, a high value of the power was also found at high frequencies. The one long trajectory showed the greatest power to be almost uniformly distributed over a surprisingly large range of low frequencies. Assuming this is a representative observation, the importance of a consistent definition of scale when measuring accelerations and related quantities is discussed.

(6) R. R. Rapp (The Rand Corporation, Santa Monica, Calif.) The Distribution of the End Points of Air Trajectories--It is assumed that the free-air wind vectors and the end points of air trajectories are distributed according to the circular Gaussian distribution. A method is devised for calculating the parameters of the trajectory end-point distribution from the wind distribution. The accuracy of the distribution function so derived is tested with computed geostrophic trajectories and with actual balloon trajectories.

(7) Charles C. Bates (U. S. Navy Hydrographic Office, Washington 25, D. C.) Report on the Recent Symposium on Interaction of the Sea and Atmosphere: A Resumé and an Outlook--The first action of the newly appointed American Geophysical Union - American Meteorological Society joint Committee on Interaction of the Sea and Atmosphere arranged and presented a symposium reviewing this subject at the April, 1954, meeting of the American Meteorological Society in Baltimore. The committee chairman comments on the results of this symposium, particularly with reference to the requirements for future work on the problem.

(8) Walter Munk (Scripps Institution of Oceanography, La Jolla, Calif.) and E. E. Gossard (U. S. Navy Electronics Laboratory, San Diego, Calif.) On Internal Waves of Five to Ten Minute Period in the Atmosphere--Oscillations of five to ten minute period have been simultaneously recorded on a barograph and wind speed and direction recorders. These oscillations are associated with propagation of internal waves centered at the inversion layer.

(9) Basil W. Wilson (Texas A. and M. College, College Station, Texas) Graphical Approach to the Forecasting of Waves in Moving Fetches--This paper describes the development and application of a graphical technique to the determination of maximum wave heights and periods attained by waves in moving wind systems. Existing deep-water forecasting data, representing the work of Munk and Sverdrup and modifications since introduced by Arthur and Bretschneider are assembled in a single chart over which a space-time wind field representing any given moving wind system (in relation to a particular point on a coast) can be placed by superposition for the evaluation of the characteristics of the waves generated at any specific point in space and time within the wind field. The space-time tracks of the waves can then be followed in their advance to the coastal station and the times of arrival, heights, and periods there determined to give in effect a synthetically constructed wave spectrum for forecasting or hindcasting purposes. The method is applicable to both approaching and receding storms and permits of decay aspects being taken into account in the usual way.

(10) Charles Cox and Walter Munk (Scripps Institution of Oceanography, La Jolla, Calif.) Some Problems in Optical Oceanography--The authors' measurements of the frequency distribution of slope (reported during last year's meeting) have made certain oceanographic problems accessible to quantitative treatment. Here we shall discuss the albedo of a rough surface from radiation of Sun and sky, the visibility of slicks on the sea surface, and the appearance of the glitter pattern from beneath the surface.

(11) Allen H. Schooley (Naval Research Laboratory, Washington 25, D. C.) Curvature Distributions of Wind-Created Water Waves--A photographic technique for determining the curvature distribution of wind-created water waves will be described. The method consists of taking photographs of the surface reflections of a light source located at the camera position. The approximate relationships between curvature, photographic image size, and the other parameters of the measuring system will be given. Plots of the relationship of curvature to wind velocity will be given for wind velocities from 0 to 20 knots.

(12) W. W. Kellogg (The Rand Corporation, Santa Monica, Calif.) The Wind Structure and General Circulation in the Upper Atmosphere--The introduction of a variety of new techniques to explore the upper atmosphere is permitting an increasingly comprehensive picture of the motions of the atmosphere to be drawn. A brief summary is made of the information presented at the National Science Foundation symposium on upper winds, held in Albuquerque in September, and some other recent data not presented at that time, and the general features of the wind structure in the upper atmosphere are described. The most striking characteristics of the wind structure are the seasonal reversals in the upper stratosphere and mesosphere, the diurnal variations in the ionosphere, and the complex and turbulent characteristics in the region between about 80 and 120 km. Finally, it is briefly shown how the wind structure deduced from observations agrees or disagrees with some more or less accepted notions based on the dynamo theory of the Earth's magnetic fluctuations and the heat budget of the atmosphere.

(13) Raymond A. Minzner (Geophysics Research Directorate, Air Force Cambridge Research Center, Cambridge, Mass.) T-Day Temperature of the Upper Atmosphere--The temperature of the upper atmosphere was measured, using five different methods on the same day, during October, 1952, at the Tularousa Basin in New Mexico. A comparison and evaluation of the results of three of these methods indicate relatively good agreement for the first successful combined operation of this kind. These methods are anomalous sound propagation, searchlight scattering, and direct rocket probing. The average temperature at the 50-km altitude is about 303°K which is 31° higher than the Rocket Panel results, and about 50° lower than the NACA tentative standard. An indication

of the sensitivity of one of the experiments, the anomalous sound propagation, is indicated by the fact that it provides the only experimental evidence of a diurnal temperature variation in the 30- to 50-km ozone region.

(14) H. Riehl (University of Chicago, Chicago, Ill.), F. A. Berry (U. S. Fleet Weather Central, Norfolk, Va.), and H. Maynard (University of Chicago, Chicago, Ill.) Exploration of the Jet Stream by Aircraft during the Winter of 1953--In an endeavor to determine the horizontal wind structure of jet streams, a series of aircraft traverses at about 30,000 ft pressure-altitude was undertaken during the winter of 1953. This report outlines the results of these flights, the maximum speeds encountered, the lateral shears on both sides of the jet axis, the distribution of turbulence, and the relation between observed winds and geostrophic or gradient wind calculation. The generation of the kinetic energy of jet streams is also considered.

(15) W. E. Knowles Middleton (National Research Council of Canada, Ottawa, Ontario, Canada) The Color of the Overcast Sky--A theory is developed for the spectral radiance of the overcast sky, and also of the top of the overcast, in terms of incident radiation, droplet size and concentration, and cloud thickness. The absorption of light by cloud water is allowed for. Some samples of highly polluted cloud water have been spectrophotometered, and calculations made which show that the absorption produces very little effect in the visible spectrum, and only a moderate effect in the ultraviolet, even for very impure cloud water. On the other hand, the color of the ground has a considerable effect on the spectral radiance of the overcast sky, and thus on its color. The color of the top of the overcast is, however, not greatly affected by that of the ground.

(16) Ross Gunn and Paul A. Allee (Physical Research Division, U. S. Weather Bureau, Washington, D. C.) A Three Thousand Cubic Meter Cloud Chamber--In order to carry forward precise measurements of droplet growth, rain formation, and electrical aspects of clouds, a surplus pressurized tank has been adapted to the production of artificial clouds. In a spherical tank 60 ft in diameter, warm artificial clouds, supercooled clouds, or ice crystal clouds may be produced that last up to one hour. Measurements made in the center of the tank are generally free of wall effects and closely approximate those made in natural clouds. Although direct refrigeration is not employed, a 1250 cubic feet per minute compressor permits adiabatic expansion of the air with sudden decreases in temperature of as much as 50°. Some of the characteristics and properties of the cloud chamber will be discussed.

(18) Heinz H. Lettau (Air Force Cambridge Research Center, Cambridge 39, Mass.) Dynamical Models for the Prediction of Air and Soil Temperature Response on Net Radiation Cycles--The theoretical and practical aspects of the problem of predicting nocturnal cooling near the earth-air interface have been widely investigated in the meteorological literature. More important to climatology is the relatively seldom discussed problem of predicting air and soil temperature response on forcing functions as given by the diurnal and annual cycles of irradiation. Any theoretical model of the process has to consider a minimum number of four physical characteristics of the problem: (1) the analytical form of the forcing function, that is, amplitudes, frequencies of a number of elementary cycles, (2) a dynamical factor as given by the general air-flow pattern, (3) physical characteristics of the earth-air interface, especially its roughness, and (4) soil-heat parameters, that is, heat conductivity and capacity.

(20) Vance A. Myers (U. S. Weather Bureau, Washington 25, D. C.) Examples in the Application of Synoptic Climatology to Hydrometeorology--Certain types of climatological problems are better approached with a synoptic method than a purely statistical method. In some instances the synoptic method resolves a problem that is insoluble by a purely statistical method. In others the synoptic method yields a faster or better solution. Illustrations are given of the treatment of climatological problems, including problems in rainfall and extremes of hurricane pressure and wind, by synoptic methods by the Hydrometeorological Section of the Weather Bureau.

(21) David I. Blumenstock (Rutgers University, New Brunswick, N. J.) Dynamic Weather Regions: Some Concepts and Examples--Inductive and deductive studies of the past ten years make possible identification of primary, secondary, and tertiary dynamic weather regions of the Northern Hemisphere. Evaluation of pertinent studies indicates that primary weather areas may be defined in terms of major circulation features, such as major sink regions or major blocking regions. Secondary weather regions might be defined quantitatively with reference to the dynamic circumstances that identify the primary region. Tertiary regions might be related to topography, for example, zones of convergence along coasts, major mountain barriers, or extensive lake areas. Such dynamic weather regions will vary in size and location with season; different criteria will have to be used for quantitative identification of different types of primary regions. These variations with season and in criteria provide the flexibility necessary in any dynamic approach to a

classification of weather regions and may permit a realistic basis if considerable reliance is placed upon inductive as well as deductive studies. The scheme must be not only correct as an approximation in the dynamic sense but also broadly descriptive of the lower troposphere where all immediate weather phenomena take place. For this reason, the criteria defining a primary region must be strongly reflected in many aspects of the weather of the region.

(22) Werner A. Baum (Florida State University, Tallahassee, Fla.) Climatic Meteorology: Some Thoughts on Methodology--Some aspects of description, explanation, and application in the field of "climatology" are considered. Wider use of new approaches, based on the known character and behavior of the atmosphere, appears called for by the shortcomings of traditional approaches. Success requires that climatology, as distinct from meteorology, die; it requires that we think of "climatic meteorology," as differing phases of one and the same field of endeavor, rather than of "meteorology" and "climatology."

(23) Woodrow C. Jacobs (Air Weather Service, Andrews Field, Washington, D. C.) The Place of Dynamic Climatology in the Meteorological Scheme--The speaker takes the premise that any name science or professional field, such as dynamic climatology, must justify itself as a reasonable distinct, definable, and useful area of activity or category of knowledge. An attempt is made to delineate and justify a dynamic climatology as a separate and useful field for research and as distinct from analyses of the mean general circulation and from such fields as synoptic climatology, physical climatology, applied climatology, etc. Some proposals for profitable areas of research in dynamic climatology are indicated.

SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY

(1) Elwood Maple (U. S. Naval Ordnance Laboratory, White Oak, Silver Spring, Md.) Sub-Audio-Frequency Oscillations of the Geomagnetic Field: 0.01 to 1 cps--Two fairly extensive experimental studies of oscillatory fluctuations (also called "micro-pulsations") of the geomagnetic field have appeared recently, and Holmberg has concluded, by a process of elimination of possible physical mechanisms from theoretical considerations, that these oscillations probably originate in magnetohydrodynamic resonance of one or more ionospheric layers, probably in the F region of the ionosphere. The experimental evidence is examined, and it is concluded that the most reasonable interpretation of the present (rather limited) data is that the oscillations between about 0.1 and 1 cps originate in the F region while the lower frequencies (0.01 to 0.1 cps) originate in the E region, some of them being associated with the normal E layer and some with sporadic E. Some of the still lower frequency oscillations (below 0.01 cps), including the "giant micro-pulsations" observed in the auroral zones, do not seem to fall within this scheme.

(2) W. E. Austin and E. Maple (U. S. Naval Ordnance Laboratory, White Oak, Silver Spring, Md.) Sub-Audio-Frequency Fluctuations of the Earth's Magnetic Field at White Oak, Maryland--Fluctuations of the geomagnetic field have been recorded on magnetic tape at White Oak, Maryland. A pick-up coil oriented in the magnetic N-S horizontal plane was used to detect the fluctuations; its output was amplified and used to frequency modulate a carrier recorded on magnetic tape. The tape was later decoded and the fluctuations were analyzed for amplitude and period by means of eight octave band pass filters covering periods from 0.25 to 66 sec. Oscillations of narrow frequency band-width were observed as well as random fluctuations. The amplitude and frequency characteristics of these phenomena, and their correlation with K indices and ionospheric data, will be discussed.

(3) John B. Wilcox and Elwood Maple (U. S. Naval Ordnance Laboratory, White Oak, Silver Spring, Md.) Audio-Frequency Geomagnetic Field Fluctuations--An investigation of the audio-frequency spectrum of geomagnetic field fluctuations as a function of time and latitude has been undertaken. Data from three stations located at Point Barrow, Alaska; Panama City, Florida; and White Oak, Maryland, have been gathered and a preliminary reduction made. Results indicate that the major source of these fluctuations is atmospherics, so that they may be considered as an entirely separate phenomenon from the lower frequency fluctuations originating in ionospheric activity. Signal strength has been found to vary approximately inversely as the first power of frequency at all three stations. Extrapolation of the curves of signal strength with frequency into the radio-frequency range yields values in fair agreement with reported atmospherics signal strengths. Extrapolating the low-frequency end of these curves yields values at 1 cps which are larger by at least an order of magnitude than those determined independently. For the three stations considered, signal strength decreases with increasing latitude, as would be expected for manifestations of thunderstorm activity and as opposed to fluctuations associated with ionospheric activity. Diurnal variations of maximum transient signals observed in ten-minute sampling periods and of the "steady" background are reported, for selected audio-frequency bands, and a point-by-point comparison of signals observed simultaneously at different stations is presented.

(4) Edwin J. Chernosky (Geophysics Research Directorate, AF Cambridge Research Center, Cambridge 39, Mass.) Twenty-Seven-Day Recurrences and Non-Recurrences in Geomagnetic Activity--A modification of the phased-superposed-epoch method of analysis is employed to make a new evaluation of the morphology of magnetic activity related to recurrent and to non-recurrent activity. To obtain homogeneous groups of any type, 36-day chronological sequences of magnetic character figures are allocated and superposed on the basis of the classification of the first and twenty-eighth value of each of the 3653 sequences. In this way individual sequences having recurrent or non-recurrent activity are identified before grouping is made. The C-figures are classified as disturbed (D) above 1.0, quiet (Q) below 0.4, and intermediate (I). Curves are given to show patterns not evidenced in the usual superposed epoch plots. For the group of ten years 1935-44 the frequency of occurrence of each combination of first and twenty-eighth day classifications, relative to the expected frequency of occurrence from random association, ranges from 152 pct for D D to 60 pct for Q D. Eighty per cent of the above excess of D D and Q Q sequences is derived at the expense of the D Q and Q D or most negatively correlated sequences.

(5) H. Freeborn Johnston (Heat and Power Division, National Bureau of Standards, Washington 25, D. C.) List of Magnetic Observatories and Thesaurus of Annual Values--At the Ninth General Assembly of the International Union of Geodesy and Geophysics, held at Brussels, Belgium, in 1951, the Association of Terrestrial Magnetism and Electricity established a Committee on Thesaurus of Annual Values at Geomagnetic Observatories. The tabulated values for current years are those that have been recently received. World-wide cooperation of observers-in-charge makes the table possible. Some of the values for the year 1953 are even included, thanks to the assiduity of the officers responsible for the reduction of magnetic data.

(6) H. W. Straley, III (Post Office Box 68, Princeton, W. Va.) Geophysical Investigations in the Southeastern States--Geophysical work has been done by various organizations along the southern Atlantic coastal plain. The University of North Carolina reported: (1) a change in basement-complex-surface gradient; (2) linear highs and lows; (3) a buried Triassic basin surrounding Florence, South Carolina; (4) a deep basin in coastal North Carolina; and (5) a depression and elevation seaward from the Eastern Granite Belt of North Carolina. Some conclusions have been verified by commercial investigations. The United States Bureau of Mines mapped Florida and Georgia, although the U. S. Geological Survey has not published the results of the latter study. Columbia, Lehigh, and Princeton Universities have done seismic work, some of which verified the gradient change in the basement complex. The U. S. Coast and Geodetic Survey made gravitational observations in Virginia, which may be interpreted in the same way as the seismic and magnetic work.

(7) Victor Vacquier and Paul R. Kintzinger (New Mexico Institute of Mining and Technology, Socorro, N. Mex.) Induced Electrolytic Polarization in Moist Clays--When a direct current carried by a moist clay specimen is interrupted, the voltage between two potential electrodes decays with a time constant which can be as long as 30 sec. The time constant is an inverse function of the conductivity and increases with the length of time the direct current is applied until a saturation time is reached. In a dissemination of one per cent clay in quartz sand, the initial polarization gradient can be as large as two per cent of the applied excitation voltage, in the range of excitation voltage of 20 millivolts per cm. This phenomenon may have an important bearing on the application of induced polarization to mineral prospecting as first suggested by D. F. Bleil.

(8) C. W. Gartlein (Physics Department, Cornell University, Ithaca, N. Y.) Correlation between K_{Ch} and Farthest South Position of Aurora--The data collected by the volunteer observers of the National Geographic Society - Cornell University Study of Aurora have been analyzed for the years 1938-1946. The southernmost latitude of overhead aurora was determined for each three-hour interval for each observer. The data were compared with the Cheltenham K figures. Correlations for forms of aurora other than G, DS, PS were obtained as follows: (1) southern extent versus K for same interval, $r = 0.68$; (2) southern extent versus K for previous interval, $r = 0.58$; and (3) southern extent versus K for next interval, $r = 0.50$. The effect of changes in K was sought but no significant conclusions could be reached. The correlation between glow and K was only two per cent.

(9) H. W. Wells (Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.) F-Scatter at Huancayo, Peru, and Relation to Radio Star Scintillations--The scattering of radio waves by the F-region of the ionosphere at an equatorial location (Huancayo, Peru) was discussed by Booker and Wells in 1938. Subsequent analysis reveals pronouncedly diurnal, seasonal, and annual characteristics. It is fundamentally a night-time event, with greatest frequency of occurrence in the period from four hours before midnight to four hours after midnight. The scattering is most prevalent during seasons when the Sun is overhead and is infrequently

observed during May, June, July, and August (local winter) when the noon solar zenith angle becomes as great as 35°. The relative total annual occurrence of F-region scatter for the period 1938 through 1945 shows low values during 1941-1942, followed by a rapid increase through 1946, which may reflect a dependence on sunspot cycle. The diurnal properties of F-scatter closely correspond to reported characteristics of radio star scintillations with peak activity around midnight. However, the annual or seasonal properties are not in simple agreement.

(10) Victor F. Hess and W. D. Parkinson (Fordham University, New York 58, N. Y.) The Contribution of Alpha Rays to the Ionization Balance of the Lower Atmosphere--Alpha-ray ionization is perhaps the most variable single component of the ionization of the lower atmosphere. Many measurements have been made to determine the ionization from airborne sources of alpha rays. This depends principally on the amount of radon and thoron in the atmosphere. An attempt is made here to evaluate the role of alpha rays originating from the surface of the ground and other naturally occurring surfaces.

(11) Ross Gunn (Physical Research Division, U. S. Weather Bureau, Washington 25, D. C.) Electric Field Regeneration in Thunderstorms--A season's record of the electric field intensity measured on the Earth during active thunderstorms is evaluated. The records show that two basic types of storms exist. The most common or positive type of active storm systematically induces positive electricity on the Earth. The normal systematic increase in electric field is interrupted and partly neutralized or over-neutralized by two types of lightning discontinuity. The most frequent electrical discharges reduce the field only by a small fraction. After four to ten fractional decreases in field, a large change is observed that frequently reverses the field. Negative storms that systematically induce negative charge on the Earth occurred infrequently, as did storms of the mixed type. The fundamental cloud-charging mechanism is formulated in quantitative terms. The analysis suggests that two basic time intervals related to the observed field discontinuities are associated with thunderstorm electricity. First, the regeneration time necessary for the falling rain to raise the electric field to the critical breakdown field for air. Second, the relaxation time required to distribute free electrical charge through the thundercloud by conduction. The regeneration time in active storms is always a fraction of the relaxation time. The quantitative formulation is compared with observed measurements made inside an active thunderstorm, and it is concluded that electrified falling rain is just adequate to describe the observed phenomena.

(12) Scott E. Forbush (Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.) World-Wide Changes in Cosmic-Ray Intensity and Their Relation to Magnetic Storms and Sunspot Numbers--A world-wide sunspot-cycle variation of about four per cent range in the annual means of cosmic-ray ionization is found from continuous Compton-Bennett meter records at Cheltenham (1937-1952), Christchurch (1938-1950), Godhavn (1939-1950), and Huancayo (1937-1952). The maximum cosmic-ray intensity occurs near sunspot minimum. At Huancayo, the variability of daily means about monthly means of cosmic-ray intensity is minimum at sunspot minimum. The greater variability at other stations is ascribed to greater variations from μ-meson decay arising from larger changes in vertical air-mass distribution. No geomagnetic storm-parameters have been found to exhibit a consistent difference for storms with and without cosmic-ray decreases. The causes responsible for the cosmic-ray changes are probably associated with the mechanism for magnetic storms but in a way not yet understood.

(13) H. K. Sen and M. L. White (National Bureau of Standards, Boulder, Colo.) Thermal Versus Gravitational Tides in the Earth's Atmosphere--The authors consider forced oscillations in a rotating atmosphere composed of a perfect gas in hydrostatic equilibrium where the forcing terms are generalized to include both solar gravitational and heating effects. The solution of the problem is obtained in terms of the χ-function (divergence of the velocities) and consists of both the complementary solution and the particular solution. The latter was found to be negligible in comparison with the complementary solution for the various atmospheric models tested and for a value of the source function of the type $e^{-\beta z}$. Values of β obtained from observations on semi-diurnal temperature variations on Pacific islands were found consistent with values found from measurements of the thermometric conductivity at the base of the atmosphere. For several different models of the atmosphere, including the NACA, it was found that the thermal effect predominated over the gravitational one. In the neighborhood of resonance, amplifications of the order of 10^4 were obtained, and, furthermore, the phase factor was essentially in agreement with the observed phase of the semi-diurnal pressure oscillation, namely, 10h 00m. It was concluded that since the theoretical amplification was so large, and, further, as the effect was thermal rather than gravitational, a sharply tuned atmosphere was unnecessary, thus overcoming the usual objection to the resonance theory of atmospheric oscillations.

(14) Joseph W. Chamberlain (Yerkes Observatory, Williams Bay, Wisc.) The Excitation of Hydrogen in Auroras--The Balmer emission produced when protons penetrate the atmosphere during an aurora is investigated theoretically. The Ha luminosity versus height, as computed for several incident proton energies, gives much narrower curves than are obtained for the luminosity distribution in other emissions. This is in accord with observations. It is found that each incident proton should produce about 50 quanta of Ha, which leads to a rough estimate for the proton flux of about 6×10^{-7} cm^{-2} sec^{-1} during the arc stage of a moderately strong aurora. The Balmer decrement has been computed, but observational material on these ratios is still lacking. A comparison of the theoretical Ha intensity profile for an arc in the magnetic zenith with Meinel's observations indicates that the radiating atoms depart appreciably from rectilinear paths along the magnetic lines of force. It is suggested that these departures are due primarily to scattering of protons and hydrogen by atmospheric collisions. These results, therefore, are not inconsistent with the hypothesis that the incident protons initially follow paths precisely along the lines of force. Careful observations of Ha on the magnetic horizon should give many of the data required for further interpretations.

(15) J. W. Dungey (Ionosphere Research Laboratory, Pennsylvania State University, State College, Pa.) Theory of Geomagnetic Micropulsations--The particular interest of micropulsations is their sinusoidal form which indicates a resonance phenomenon. Resonance can be obtained from standing Alfvén waves which follow the lines of force and are reflected at the ground. A rough estimate of the period of the fundamental can be obtained from Storey's value of the electron density in the outer atmosphere assuming this to be hydrogen. Neglecting the effect of the ionosphere, the period is found to be roughly $0.5 (\cos \theta)^{-8}$ sec, where θ = magnetic latitude. The effect of the ionosphere has been worked out for periods of about one minute; the kind of wave propagation varies with height but the net effect is a damping comparable to that due to imperfect reflection at the ground; there is an appreciable difference between the two circular polarizations. At lower latitudes the ionosphere is more important and increases the period. Micropulsations have usually been observed just outside the auroral zones, but can be detected with more sensitive equipment at other latitudes. The observation of radio echoes from above the F layer pulsating with the field shows that the upper atmosphere is involved. Further work may yield information about the outer atmosphere and possibly about the nature of the auroral zones.

(16) Vaughn Agy (National Bureau of Standards, Washington 25, D. C.) Variations in the Probability of Occurrence of Polar Blackouts--Tabulations of hourly values of the ionospheric parameters for 18 northern hemisphere stations have been used to derive diurnal variations in the occurrence of "blackout" conditions. Geographic contour plots of the "probability" of occurrence are presented showing the average value, the amplitude of the diurnal variation, and the time of maximum probability. Changes in the contours with season and with magnetic activity are discussed. Shortcomings in the method are emphasized and further studies are mentioned which may lead to conclusions of greater reliability and usefulness.

(17) C. W. Gartlein (Cornell University, Ithaca, N. Y.) The Southern Side of the Overhead Auroral Zone--Data on occurrence of aurora have been collected since 1938 from a group of volunteer observers in northern U. S. and southern Canada. The data for the six years 1947-1952 are here considered. They are sufficiently complete that the southernmost latitude of overhead occurrence could be determined for most nights. When an observer was not located under the most southern position, this position was calculated from the angular heights given by observers and from the assumed height of 100 km. These data were tabulated for various zones of geomagnetic latitude for each year. The data for zones south of a given zone were added to the data of the given zone to give the overhead frequency. This gives the average shape of the southern side of the auroral zone. If we take the zone 64-66° geomagnetic as 100 pct, then for 58-60° we get 47 pct; for 54-56° we get 8 pct, while for south of 53° we get 0.4 pct.

(18) A. M. Peterson and R. L. Leadabrand (Radio Propagation Laboratory, Stanford University, Stanford, Calif.) Long-Range Radio Echoes from Auroral Ionization--Radio echoes believed to be from auroral ionization are consistently observed at Stanford University. These echoes are unusual for several reasons. First, the ranges at which they are observed (1600-4700 km) are much greater than ranges previously reported. Second, the observation frequencies of 6.425 mc, 12.8625 mc, and 17.31 mc are lower than those previously used for auroral work. Third, the height above the Earth at which reflection is believed to take place is greater than the height at which auroral reflections are commonly thought to occur. Fourth, the strength of the echoes is surprisingly great, being frequently greater than the strongest F layer propagated ground scatter echoes occurring at the same time. Auroral echoes of this type are readily distinguishable from ground scatter echoes by consideration of their bearing, echo shape, amplitude fluctuation, Doppler shift, and time

of occurrence. Previous radio observations of the aurora have been made at locations much farther north geomagnetically (53-67°) than Stanford University (43.7°). It is believed that in some respects observations at the lower latitudes may give a more complete picture than can be obtained at locations nearer the auroral zone. At Stanford the echoes have been observed at ranges and bearings which indicate reflection from ionization at points along the auroral zone all the way from eastern Canada to Alaska.

(19) K. L. Bowles (Geophysical Institute, University of Alaska, College, Alaska) VHF Auroral and Meteor Echoes Including Simultaneous Observations--Auroral echoes have been observed at College, Alaska, using SCR270 radar at 106 mc/sec. The location of College close to the center of the auroral zone makes these observations unique, since visible aurora is commonly seen in all directions of azimuth as well as overhead. Similar to previous results, (1) echoes are found only within a sector slightly wider than one quadrant, centered on geomagnetic north, (2) ranges between approximately 500-1000 km are found, and (3) no vertical incidence echoes may be obtained from the various forms of aurora when seen overhead. These observations are seen to conform with the meteor trail analogy for VHF aurora echoes as postulated by R. K. Moore. An interesting observation, though not substantiated by a large amount of data, is that the rate and strength of meteor echoes is considerably enhanced during periods when aurora is seen in the sky. The normal rate of three to five echoes per hour is increased to as much as 25-30 echoes per hour. No indication of preferred azimuth is found. In the meteor echo after the initial whistle has ceased, the fading rate fits in with results of other workers but is an order of magnitude slower than fading found in auroral echoes.

(20) R. Dyce (Cornell University, Ithaca, N. Y.) Auroral Echoes of Fifty Megacycles Obtained at College, Alaska--CW and pulse methods were used to study returns from the aurora at 50 mc/sec during the summer of 1953, the equipment being located near the center of the auroral zone. Aurora was frequently seen in all parts of the sky but the VHF echoes were obtained only from azimuth angles within 60° of magnetic north and with ranges of from 200-900 km but chiefly 400-700 km. A vertically-pointing antenna was used in an attempt to obtain echoes from overhead visible aurora but results were negative. Most of the echoes were therefore originating far north of the zone of maximum auroral activity. These data support the view that strongest echoes will be obtained when looking roughly perpendicular to the Earth's magnetic field. CW signal-strength recordings with antenna directed northward yield a diurnal variation for auroral propagation similar to results obtained at Ithaca, New York.

SECTION OF OCEANOGRAPHY

(1) Edward L. Corton, Jr. (Division of Oceanography, U. S. Navy Hydrographic Office, Washington, D. C.) A Study of the Arctic Ice Pack--The annual cycle of the Arctic ice pack is considered from the viewpoint gained by aerial reconnaissance. The composition of the pack during summer months is 75 to 85 pct polar ice and ten to 20 pct winter ice. About ten per cent of the total volume of the ice flows out of the polar basin annually. The average age of the polar ice is about nine years, but 11 pct of it is over 20 years old. The total concentration of ice in summer is highest (98 pct) between the North Pole, Spitzbergen, and Greenland, and the average age of the polar ice is greatest there. Between the Laptev and Beaufort Seas the summer coverage is lower (90 pct), the percentage of winter ice higher, and the average age of the polar ice lower. Forecasting the movements of the ice pack involves consideration of the composition of the pack as well as wind and current factors, because of the different physical characteristics of winter and polar ice. If the warming of the Arctic in this century continues, the oceanographic factors should lead to complete melting of the permanent ice pack and marked changes in polar climate.

(2) J. R. Gerhardt, K. H. Jehn (Electrical Engineering Research Laboratory, University of Texas, Austin, Texas), and I. Katz (Applied Physics Laboratory, Johns Hopkins University, Silver Spring, Md.) A Comparison of Step, Pressure, and Continuous-Wire Gage Wave Recordings in the Golden Gate Channel--Step, pressure, and continuous-wire type wave gages were installed on a steel piling located in some 35-40 ft of water approximately 600 ft off the northeastern end of Baker's Beach in the Golden Gate channel. Simultaneous measurements from all gages were made on a nearly continuous basis during April, 1953. These data have been evaluated to obtain characteristic wave periods and amplitudes, amplitude probability distributions, autocorrelation functions, and power spectra. In addition, direct recordings of wave slopes were made possible by using a three-wire continuous-wire gage and a brief description is given of certain of the characteristics of these data. While the frequency responses of all three instruments were nearly identical, surface waves derived from the sub-surface pressure gage recordings were shown to underestimate true values by an average factor of about 25 pct. The rather complex oceanographic structure of

the channel is emphasized by occasional well-marked surges having periods of about three minutes with amplitudes up to one foot and by the significant changes occurring in the characteristic wave period which were not confirmed by Light Ship measurements made off the channel in open water.

(3) Walter Munk, June G. Pattullo, Roger R. Revelle, and Elizabeth Strong (Scripps Institution of Oceanography, La Jolla, Calif.) The Annual Change in Sea Level--A chart has been prepared showing seasonal changes in sea level on a global scale on the basis of all published tide-gauge recordings (about 10^5 values). It is found that on the average sea level is higher in both hemispheres in fall than in spring by something like one-half foot. A comparison with changes in "dynamic" height (as derived from all suitable BT soundings now on file) indicates that sea-level changes are baroclinic in low latitudes but not in high latitudes. There is some weak evidence that the oceans as a whole contain 5×10^{18} grams less water in spring than in fall. The phase and order of magnitude of this term is in accord with estimates of water storage on continents in the form of snow and ground water.

(4) Frank Snodgrass and Walter Munk (Scripps Institution of Oceanography, La Jolla, Calif.) Measurements of Long-Period Waves Offshore--A Vibrotron pressure transducer placed on the sea bottom is used to record very small changes in sea level. With the instrument placed at 500 ft it has been possible to obtain an accuracy of one millimeter of water pressure for a measurement extending over ten seconds. The instrument is capable of recording waves of periods of one second and longer. The principal purpose at present is to study the behavior of surf beat (one- to two-minute period) and of 15- to 20-minute waves offshore.

(5) Paul Ferris Smith, Joseph D. Richard, and Frank H. Stephens (Marine Laboratory, University of Miami, Coral Gables, Fla.) A Technique for the Spectral Analysis of Sound in the Ocean--A method is given for presenting a continuous quantitative spectrum of sound in the ocean. A more detailed spectrum is obtained than from previous methods with the advantage of convenient and rapid operation. The technique has proved useful in the analysis of sub-surface oceanic sounds of meteorological and biological origin, examples of which are given, and will facilitate the analysis of other oceanographic noise spectra such as those of volcanic origin. The method is based upon a modification and adaptation of a commercially-available heterodyne type sonic analyzer with cathode-ray tube presentation. Provisions for photographic recording have been added.

(6) Tsaihwa J. Chow and Thomas G. Thompson (Department of Oceanography, University of Washington, Seattle, Wash.) Seasonal Variation in the Concentration of Copper in the Surface Waters of San Juan Channel, Washington--The concentration of copper in the surface water of San Juan Channel in the State of Washington was determined over a period of 17 months. The average concentration of copper in all samples analyzed was 0.023 μg-at/L. A definite seasonal trend was indicated with an autumn minimum of 0.016 μg-at/L Cu and a summer maximum of 0.028 μg-at/L Cu. The copper content varied inversely with the values obtained for density, phosphates and silicates.

(7) Joseph Bernstein (U. S. Navy Hydrographic Office, Washington, D. C.) The Progressive Decline in Level of the Caspian Sea--The persistent decline in level of the Caspian Sea has had serious effects on major Russian industries, such as oil, shipping, fishing, and chemical. Since 1929, the level has been steadily declining and is now the lowest it has reached in the last 400 years. It is now 92 ft below ocean level, and there is no indication that equilibrium is approaching. The Caspian, together with the Black and Aral Seas, was originally part of one body of water. At the end of the glacial period, separation occurred, and the Caspian has been shrinking ever since. Large areas, formerly covered by water, have recently become dry land, particularly in the northern and eastern parts. Explanations involving climatological changes, tectonic movements, and increased land and water utilization have been invoked. These theories are evaluated, the last offered as most plausible. Large canals to rescue the Caspian were started and recently abandoned.

(8) N. P. Fofonoff (Brown University, Providence, R. I.) Steady Horizontal Motion in a Frictionless Homogeneous Ocean--A mathematical model is developed to study the free, steady, horizontal motion which can occur in a homogeneous, frictionless ocean of constant depth. From the analysis of this model it is concluded that in an enclosed ocean a free, steady circulation, satisfying the dynamic constraint that the vertical component of absolute vorticity is constant along a streamline, cannot have any slow, broad eastward currents. The eastward currents must occur as narrow streams of high velocity and high relative vorticity. Intensified currents are found to be present along both the western and eastern coasts. The results obtained using this model are useful in interpreting the behavior of ocean current systems such as the Gulf Stream.

(9) D. W. Pritchard (Chesapeake Bay Institute, Johns Hopkins University, Annapolis, Md.) A Study of Flushing in a Model of the Delaware Estuarine System--A description is given of a series

of flushing tests utilizing the model of the Delaware estuary located at the U. S. Army Engineers Waterways Experimental Station, Vicksburg, Mississippi. A tracer dye was introduced into the model at selected locations and the change in concentration of the dye contaminant was followed as the contaminated volume spread out and moved down the estuary. A preliminary analysis of the data indicates that the decrease in peak concentration is exponential with time. The "diffusivity" increases as the square of the standard "spread" of the contaminant.

(10) Kozo Yoshida and Han-Lee Mao (Scripps Institution of Oceanography, La Jolla, Calif.) Upwelling off the California Coast--An attempt is made for estimating upwelling velocity off the California Coast from available oceanographic data. The method is essentially based on derived relations between vertical velocity and the distributions of mass and stress. In order to ascertain the reality of computed results, it has been tried as extensively as possible to compare our results with information obtained by other means. It appears that upwelling depends largely upon the variabilities in surface meteorological conditions and the reliability of the results should somewhat be limited owing to the uncertainties involved in our available data. Upwelling of local or temporary occurrence is also discussed briefly. Although the computations are based on the data in California waters, the method could be applied to other areas. It is suggested that vertical velocity at intermediate levels below thermocline, say 150 m level, can well be indicated by the "east-west difference in density at a deeper level such as 800 m level in our areas."

(11) Harold Flinsch (Mississippi State College, State College, Miss.) The Effect of Deep-Water Waves on the Contours of Sand Beaches--During the summer of 1953, the author observed a certain peculiar dependence of the contours of the sand beaches of Nova Scotia upon the magnitude and direction of energy of the larger waves in the Bay of Fundy and the Gulf of Maine. Combined with the previously discovered stability of a beach slope, the observation that a stable beach is always aligned at right angles to the average direction of wave energy was confirmed by measurements on the beaches of Cape Breton Island, facing the Atlantic Ocean and the Gulf of St. Lawrence, and on the Atlantic Ocean beaches from Cape Cod to Miami. A new approach was necessary for the Atlantic coast of the United States, wherever a beach is exposed to considerable wave energies from several directions, such as at Cape Cod and Cape Hatteras. With the aid of charts of the prevailing energy of waves along the coast, the curvature and development of beaches consisting of movable material can be determined.

(12) Robert G. Paquette and Clifford A. Barnes (Department of Oceanography, University of Washington, Seattle, Wash.) Some Characteristics of Currents in Deep Inshore Waters--Results of a number of direct current measurements made at various depths in Puget Sound during the years 1949-1953 are interpreted in terms of time-average currents. The upper levels are characterized by an excess of ebb over flood whereas in the deeper water, below an intervening zone of no average net motion, flood predominates over ebb. At depth relatively strong currents approaching surface velocities occasionally extend to within a meter or less of the bottom. Some of the relations of the currents to the accompanying water structure are discussed.

SECTION OF VOLCANOLOGY

(2) Francis R. Boyd (Geophysical Laboratory, Carnegie Institution of Washington, Washington, D. C.) Volcanic History of a Portion of the Yellowstone Park Rhyolite Plateau--A reconnaisance made in connection with some detailed petrologic and volcanologic studies in Yellowstone Park permits the outlining of the volcanic history of a considerable portion of the rhyolite plateau. The types of volcanic rocks found in the plateau are, in order of abundance: rhyolite flows, welded rhyolitic tuff, basalt, rhyolite dome lavas, and mixed rhyolite-basalt lavas. No intrusive rhyolite has been observed in the Park in this investigation, with the possible exception of the rhyolite of the Gardiner River Complex. Pyroclastic rocks other than welded tuffs are of minor importance. A number of vents have been located, but major volcanoes do not appear to have been built during the eruption of the volcanics in the plateau. The rhyolites are divisible into three main stratigraphic units. The oldest rhyolites are flows whose base is not exposed. These flows are overlain by extensive deposits of welded tuff. The youngest rhyolites, a series of enormous flows, were erupted on the eroded and faulted surface of the welded tuff. These flows cover a third of Yellowstone Park. Individual flows range from 100 to 1000 ft in thickness and spread over areas as large as 100 sq mi.

(3) F. Chayes (Geophysical Laboratory, Carnegie Institution of Washington, Washington, D. C.) Potash Feldspar as a By-Product of the Biotite-Chlorite Transformation--Granules of potash feldspar occur in the biotite and chlorite of many calcalkaline granites. In the granite of the Sierra de Guadarrama, exposed north of Madrid, these granules are rather rare in biotite, considerably more frequent in chloritized biotite, and common in chlorite. They are evidently a by-product of the biotite → chlorite transformation, although the amount of potash they contain must be only a small part of that

released in the course of the reaction. From the distribution of feldspar granules it is argued that all the chlorite of this rock, including euhedral flakes showing no trace of biotite, is a replacement of biotite. The erratic distribution of chlorite itself is most easily accounted for by hydrothermal action.

(4) Garniss Curtis, Howel Williams (University of California, Berkeley 4, Calif.), and Werner Juhle (deceased) Evidence against Assimilation of Andesite by Rhyolite in the Valley of 10,000 Smokes, Alaska--Mt. Katmai and the great "sandflow" in the Valley of 10,000 Smokes were examined by the authors during the summer of 1953. No evidence was observed to support the hypothesis of a still under the valley floor. Instead, radiating and concentric fissures about the dome of Novarupta suggest that a near vertical conduit there was the source of most of the material composing the sandflow. It is improbable that the great number of banded pumice fragments throughout the sandflow were formed by partial assimilation of morainic andesitic debris covering such a small area. Transitional stages of "assimilation" of andesite are conspicuously absent. Boundaries between streaks of andesitic and rhyolitic glasses are usually sharp, gradations being but a few microns thick. Partly fused plagioclase crystals (An_{60-80}) in the andestic streaks are often adjacent to sharply euhedral crystals of plagioclase (An_{37-41}) in the rhyolitic streams, therefore it is unlikely that the rhyolite magma was the source of heat for the fusion. The authors believe that most of the phenomena attributed by Fenner to assimilation of andesite by rhyolite are better explained by mixing of rhyolite and andesite magmas, some of the partly crystallized andesite magma having been reheated shortly before mixing and eruption.

(5) Robert W. Duschatko and Arie Poldervaart (Columbia University, New York 27, N. Y.) Spilitic Intrusion near Ladron Peak, Socorro County, New Mexico--A suite of highly altered spilitic rocks from a sheet 100-150 ft thick in the Yeso formation is described. There are many similar intrusions throughout the region. The alteration process is traced in detail. The trend of alteration is toward the production of minerals containing only one metallic element in addition to H, Si, and Al. Deuteric alteration is probably accentuated by distillation of hyperfusibles, especially sulphate radicles, from the country rocks, which include much gypsum. Fine-grained albitites are the end-products of differentiation, and zircon studies indicate that these rocks are partly of magmatic, partly of metasomatic origin. The basaltic rock types contain very few skeletal zircons. Coarse-grained quartz-feldspar rocks along the margin of the intrusion show features indicative of recrystallization and replacement in the country rocks.

(6) E. Wm. Heinrich, Lewis B. Kellum, and Robert Linsley (University of Michigan, Ann Arbor, Mich.) Volcanic Rocks of the Sierra de Tlahualilo, Durango, and Coahuila, Mexico--Across the Durango-Coahuila border in north-central Mexico, near Torreon, and on the west side of the Sierra de Tlahualilo, are two areas underlain by volcanic rocks. The rocks, which lie on folded and eroded Cretaceous limestones, consist of both flows and pyroclastics, including volcanic ash, and are rhyolitic, andesitic, and basaltic in composition. A basal group consists of alternating rhyolitic and andesitic tuffs and flows, and is overlain by thick rhyolitic tuffs and flows, including a pitchstone. Above these is a light-colored ash, capped by andesitic and basaltic flows. Despite their post-orogenic age, some structural control has localized the volcanics and structural-physiographic features have aided in preserving them. Nearly all the rocks contain numerous xenoliths of Cretaceous limestone and various metamorphic rocks of Permian age, which crop out in the southern part of the range. Green, cryptocrystalline reaction rims surround the limestone xenoliths.

(7) George C. Kennedy (Institute of Geophysics, University of California, Los Angeles 24, Calif.) Causes of Explosive Eruption of Volcanoes--Explosive volcanic eruptions can only take place when the strength or weight of the rocks overlying a magma chamber is exceeded by the vapor pressure of the magma or of wet sediments surrounding the magma. Four different mechanisms can cause these conditions: (1) rapid intrusion of a wet magma to a near-surface environment; (2) rapid intrusion of a magma into a near-surface wet sediment; (3) second boiling-point phenomenon by which crystallization of anhydrous phases builds up the vapor pressure of a melt until explosive eruption takes place; and (4) diffusion of volatiles in a recently intruded column of melt to set up an osmotic pressure equilibrium gradient.

The possibility of exothermic reactions playing any important role seems so slight as to be virtually excluded. These mechanisms permit only a single explosion at a volcanic eruption whereas most eruptions are marked by a series of violent explosions. The detailed history of an eruption therefore is presumed to be controlled by sporadic nucleation of gas bubbles in a melt supersaturated with volatiles in a low external pressure environment. Nucleation of gas bubbles is essentially an antithermodynamic process. Bubbles below a critical size are unstable and grow only with increasing free energy. Above the critical size they grow with decreasing free energy and are stable. The critical size of bubbles for a given set of magmatic conditions may be readily calculated. The critical size for bubbles in a melt which has internal vapor pressure 500 bars higher than external vapor pressure is approximately 10^{-6} cm. The mechanics of nucleation and bubble propagation is discussed.

(8) Howard A. Powers (U. S. Geological Survey, Denver Federal Center, Denver, Colo.) Some Characteristics of Basaltic Magma in Hawaii--The concept of one magma, undergoing differentiation, appears inadequate to explain Hawaiian volcanology and petrology. Each volcano, regardless of its relative age, has passed through about the same pattern of eruptive and magmatic behavior. Most of the lava is erupted during a primitive shield-building stage in voluminous flows separated by short intervals of time. The rock, common to all shields and to all exposed depths in dissected shields, has the composition of equal parts of labradorite and magnesian pyroxene and variable small amounts of iron oxides and free silica. Though saturated with silica, the rocks contain five to 15 pct of olivine, quenched before its expectable conversion to pyroxene took place. During declining and decadent activity, relatively minor amounts of lava, undersaturated in silica and ranging from porphyritic basalt to trachyte, were erupted at long intervals of time. To produce the change -- from silica-saturated shield-building magma to a magma deficient in silica -- by movement of olivine and hypersthene crystals, either potential olivine must remain liquid while hypersthene crystallizes, or olivine crystals must remain suspended in the liquid while hypersthene sinks. This seems improbable. A process of successive selective meltings that yield magma progressively poorer in silica is being investigated.

(9) Matt Walton (Yale University, New Haven, Conn.) Granite Magma and Granitization in the Emplacement of "Granite"--A simple statement of the granite problem develops from the idea that most granite is formed in geosynclinal belts by equilibriopetal processes in which crustal materials attain a configuration of greater thermodynamic stability following orogenic dislocations in the P-T environment. Alkalis and some other components of granite are less stable than ferromagnesians in solid phases in higher P-T regions, so a potential exists for relative migration of granite-forming elements from such regions. Theoretically this potential can motivate either processes of diffusion and metasomatism or the formation, migration, and resolidification of separate fluid phases. The distinction is drawn between demonstrating a potential and showing what process it effectively drives. The problem is to define the limiting conditions for these processes, and establish rigorous criteria for them. In regionally metamorphosed terrains there is strong evidence for granitization, but magmatic emplacement is not excluded. In unmetamorphosed terrains energy relations prove that most, if not all, granite is magmatic. The concept of harmony between granite and its enclosing rocks, indicated by the contact metamorphic effects of the granite in relation to the regional level of metamorphism, provides a basis for defining certain limiting conditions for metasomatic and magmatic processes.

(10) Donald E. White (U. S. Geological Survey, Menlo Park, Calif.) The Violent Mud Volcano Eruption of Lake City Hot Springs, Modoc County, California--On March 1, 1951, a group of hot springs and mud volcanoes in northeastern California burst into spectacular eruption. The disturbed area included about 20 acres and involved at least 300,000 tons of mud. The most intense phase of the eruption persisted less than 12 hours. Large amounts of thermal energy may be stored in a spring system because of the increase in boiling point of water with depth, as a function of hydrostatic pressure. Thermal spring systems with temperatures near theoretical boiling points at depth are metastable, with excess energy evolving continuously as steam. Systems in well-fractured competent bedrocks are relatively stable but those in fine-grained sediments may erupt. It has been calculated that the Lake City eruption involved many times the energy of any single eruption of other known mud volcanoes, or of Yellowstone geysers, but is comparable to a single eruption of the former Waimangu geyser in New Zealand. Hot spring eruptions are related to, but distinct from, true volcanic eruptions involving direct release of energy from new magma. The energy of some volcanic eruptions may be augmented considerably by previously stored energy of near-surface hydrothermal systems. The Rotomahana phase of the great Tarawera eruption of New Zealand is suggested as an example.

(11) N. Efremov (1061 Intervale Avenue, New York 59, N. Y.) Phenomenon of Polar Isomorphism in Terms of Lattice Energies--Pairs of ions such as $Na^{\cdot}$ - $Ca^{\cdot\cdot}$, $Ca^{\cdot\cdot}$ - $Y^{\cdot\cdot\cdot}$, $Mg^{\cdot\cdot}$ - $Sc^{\cdot\cdot\cdot}$, $Sc^{\cdot\cdot\cdot}$ - $Zr^{\cdot\cdot\cdot\cdot}$ are situated along diagonals in the Periodic System of Ions and connected by some regularities. At the same time these pairs, as we know, are classical examples of isomorphous substitutions of ions (phenomenon of so-called polar isomorphism) in crystalline lattices (for example, Na - Ca in plagioclases, Ca - Y in yttrofluorites, Mg - Sc in magnesian silicates, Sc - Zr in thortveitites, and K - Ba in orthoclases). In a majority of cases of polar isomorphism the valence of substituting ions is usually higher by one than the valence of the substituted ions (for example, $Na^{\cdot}$ - $Ca^{\cdot\cdot}$, $Ca^{\cdot\cdot}$ - $Y^{\cdot\cdot\cdot}$, $Mg^{\cdot\cdot}$ - $Sc^{\cdot\cdot\cdot}$, and $Sc^{\cdot\cdot\cdot}$ - $Zr^{\cdot\cdot\cdot\cdot}$). According to our calculations there is a simple regularity connecting these diagonal rows of ions substituting each other: The EKs$^{XX)}$ for these ions are related as squares of their valence, for example: EK($Na^{\cdot}$) : EK($Ca^{\cdot\cdot}$) : EK($Y^{\cdot\cdot\cdot}$) = 0.45 : 1.80 : 4.05 = $1^2 : 2^2 : 3^2$, ... (EK, a concept introduced by Fersman, is an empirical constant for each ion, representing the contribution of that element to the lattice energies of its compounds.) When we consider the phenomena of isomorphism in terms of lattice energies, we can

see that the sense of these polar substitutions of ions is the increase of energy of crystalline lattices as the result of substitution of an ion with lower valence by one with higher valence.

(12) L. F. Herzog, W. H. Pinson, and P. M. Hurley (Department of Geology and Geophysics, Massachusetts Institute of Technology, Cambridge, Mass.) Isotopic Variations in Strontium: I, Preliminary Survey--Facilities for nuclear geophysics research at MIT have been augmented by the construction of two six-inch radius, 60° mass spectrometers for isotope analysis of solids and gases. A preliminary survey of materials expected to show variations in strontium isotope abundances has been made. Samples include: a $SrCO_3$ interlaboratory standard; celestites and limestones of different ages and origins; Rb-rich micas such as lepidolite; old calcic fledspars; a chondritic meteorite of normal composition and an achondrite with a much greater Sr/Rb ratio; and "tracer" Sr of unusual isotopic content furnished by the Atomic Energy Commission. Strontium ions are produced by heating SrO on Ta filaments and analyzed by means of a double collector specifically designed for Sr or by measurement of single collector magnet sweep records. Ion exchange columns have been set up to aid in sample preparation, and monitored by optical spectrograph. Contamination tests of all procedures have been made using isotope dilution methods. Analyses of Sr and Rb are made by isotope dilution mass spectrometry, optical spectrograph, and flame photometer. It is apparent that the variation in relative ^{87}Sr abundance in so-called "normal" strontium during geologic time is much smaller than geochemical predictions indicated and that extreme precision in mass spectrometric isotope analysis is necessary if such variations are to be useful for geologic age determination.

(13) W. H. Pinson, Jr. (Department of Geology and Geophysics, Massachusetts Institute of Technology, Cambridge, Mass.) Trace-Element Composition of a Carbonaceous Chondrite--H. C. Urey has suggested that the rare carbonaceous chondrites may be more representative of fundamental cosmic material than ordinary chondrites, which comprize the bulk of stony meteorites. The Mighei, Ukraine, carbonaceous meteorite was analyzed spectrographically, using the carefully studied Homestead meteorite as a comparison standard. Only this single specimen of rare carbonaceous chondrite was available for analysis.

Meteorite	Li ppm	Na ppm	K ppm	Rb ppm	K/Rb wt pct
Homestead	2	8300	1100	12	85
Mighei	0.5	1000	150	3	50

The major elements Si, Al, Mg, Fe, and Ca in the two specimens appeared nearly identical within the limits of spectrographic error (± 15 pct). The trace elements Ti, Mn, Ba, Sr, Cr, Zr, and Sc were likewise identical within limits of error. The silicate phase of chondrites is known to be remarkably uniform in both major and minor element content. The Mighei carbonaceous chondrite examined is of nearly identical major and minor element composition to ordinary chondrites with the noteworthy exception that the alkali metals are present in lesser concentrations by factors of four to ten. On the assumption that carbonaceous chondrites (rich in carbon, as are the comets) are more representative cosmic material than are ordinary chondrites, the cosmic abundances of the alkali metals may be even lower than is currently thought, and their abundance ratios may be different. For example, the ratio K/Rb may be nearer 50 than 100.

(14) H. A. Slack and W. C. Krumbein (Northwestern University, Evanston, Ill.) Measurement and Statistical Evaluation of Low Level Radioactivity in Rocks- Many rocks show a low level of radioactivity as measured by alpha-particle emission. Emphasis seems to have been largely on study of higher levels of radioactivity, and it is perhaps desirable to investigate activity nearer the threshold level. Basic methodology for measuring and evaluating these lower levels is developed. Statistical tests show that counting observations are samples drawn from populations distributed in accordance with the Poisson law. Confidence belts may be set up to distinguish low threshold activity from background; and to distinguish between different degrees of radioactivity in samples at selected levels of significance. Applications are made to black shale, which range in radioactivity from about 0.07 to 1.6 alpha particles per minute per square centimeter of powdered surface. Use of statistical design in extending the method to a study of regional radioactive variation within a stratigraphic unit is touched upon.

(15) Robert J. Uffen (University of Western Ontario, London, Ontario, Canada) A Method of Estimating the Thermal Conductivity of the Earth's Mantle--A knowledge of the variation of the thermal conductivity in the Earth's mantle is important for any theory of the Earth's thermal history. Using Debye's theory of the thermal conductivity of solids, seismic data, and recent estimates of the temperature variation, the ratio of the lattice conductivity at any depth to that at 100 km depth is computed. It is found that the lattice conductivity and diffusivity increase between the surface and the bottom of the mantle by factors of approximately eight and four respectively.

(16) G. J. Wasserburg (Institute for Nuclear Studies, University of Chicago, Chicago, Ill.) and R. J. Hayden (Argonne National Laboratory, Lemont, Ill.) A^{40}-K^{40} Age Determinations--A^{40}/K^{40} ratios of some presumably dated rocks and minerals have been measured using an isotopic dilution technique to determine the radiogenic argon content. The sample is dissolved in molten NaOH at 600° C and A^{38} tracer is added. After 24 hours the evolved gases are purified and the unreacted rare gas fraction analyzed by means of a mass spectrometer with 12-inch radius of curvature and 60° deflection. In order to determine whether the reaction is complete, various sieve fractions of a sample of microcline ranging from 18 mesh to 180 mesh were run. The A^{40}/K^{40} ratios determined agreed to within better than five per cent. One sample was run using molten Na_2CO_3 at 900° C as a flux. The result agreed within two per cent with the value obtained using NaOH. Two samples of feldspar from Blackstone Lake Pit, Conger Twp., Parry Sound, Ont., were analyzed. The feldspars were a microcline and an albite containing 12.1 pct and 1.30 pct K respectively. The A^{40}/K^{40} ratios obtained were 0.0514 ± 0.001 and 0.0492 ± 0.001 respectively. Using a branching ratio of 0.126 an age of 6.9×10^8 yr is obtained. The various Pb-U ages for this locality agree at 10^9 yr. Other samples from Essonville, Ont., yield an A^{40}-K^{40} age of 7.0×10^8 yr while the Pb-U ages determined on zircons by C. Patterson give an age of 10^9 yr for this locality. This discrepancy may be due to either A^{40} loss due to diffusion or to an error in the branching ratio. Using a branching ratio of 0.08 the above A^{40}-K^{40} ages can be brought into close agreement with the assumed Pb-U ages.

(17) Robert Balk (New Mexico Bureau of Mines and Mineral Resources, Socorro, N. Mex.) Kimberlitic Tuff Plugs in Northeastern Arizona--In northeastern Arizona, about 40 miles northwest of Gallup, New Mexico, the flat-lying Paleozoic and Mesozoic sediments of the Colorado Plateau are pierced by at least three vertical plugs of kimberlite tuff. The largest, Buell Park, is about 1.5 miles in diameter, the smallest only 200 ft. Undisturbed vertical contacts are locally exposed, lacking any contact effects upon the sandstone wall rocks. Layers of tuff and xenoliths, vertical along contacts, flatten inward, and lie nearly horizontally in several places. Pale green and amber olivine (fa_{7-9}), enstatite, pyrope garnet $(n = 1.744 - 1.746)$, chrome diopside, emerald-green actinolite, magnetite, titanoclinohumite, black spinel, ilmenite, and other mafics are the most important minerals, listed in approximate order of decreasing abundance. Antigorite extensively replaces olivine, and constitutes a large volume of the tuff. Sepiolite sheets veneer inward-dipping funnel fractures near the plug borders. Cognate xenoliths of peridotite are locally abundant. The Buell Park plug is, in turn, pierced by dikes and plugs of minette which has vitrified the sandstone walls in places. Both rocks were probably extruded in late Tertiary (Pliocene?) time.

(18) David Schulz (Princeton University, Princeton, N. J.) A Study of Thermal Convection and Its Possible Relation to the Circulation of Fluids in the Earth--Thermal convection in water and its modification by unconsolidated sediments were studied to determine conditions under which convection may occur in water-saturated rocks. Variation of critical temperature gradient necessary to start convection in water, dependence of this gradient upon height of water column, and effect of rate of heating, of the area of the experimental tank, and of temperature gradient before heating were evaluated. The results of the experiments indicate that the gradient necessary to start convection in water decreases rapidly as the height of the column rises from zero to two centimeters. Between a height of two centimeters and forty centimeters, the rate of change is much smaller, the necessary temperature difference dropping from 0.145° C to 0.067° C. The rate of heating and area of the tank exercised only a slight effect upon these values. Introduction of sediments into the apparatus increased considerably the temperature gradient necessary to start convection, the increase being greater the finer the grain size. The present data indicate that convection cannot exist in sedimentary rocks under normal temperature gradients, since a temperature gradient of at least 300° C/100 ft would be required to start convective overturn. Presumably such a gradient could, however, be found near an intrusive body.

SECTION OF HYDROLOGY

(1) G. E. Manger (U. S. Geological Survey, Washington 25, D. C.), G. L. Gates (U. S. Bureau of Mines, San Francisco, Calif.), and R. A. Cadigan (U. S. Geological Survey, Grand Junction, Colo.) Progress Report: Original-State Core Studies--Original-state core studies are underway to provide basic data on physical and chemical properties of uranium-bearing and adjacent country rock where the amount and composition of the interstitial water have not been changed radically by the flushing action of a water-circulating drilling medium. Core samples have been obtained by drilling with oil-base mud and air as coolants. Samples were sealed in the field to avoid loss of interstitial contents. Rock with and without interstitial solutions has been subjected to an extensive series of physical tests; pore water has been subjected to chemical tests. Results show that the

uranium-bearing rocks are characterized by distinctive values of physical properties, but relative rather than absolute magnitude of the physical properties in uranium-bearing rock compared to adjacent rocks is diagnostic. Radioactivity shows direct relationship to increased spread of grain size (standard deviation) and increased pore-water content; it shows inverse relationship to permeability, concentration of grains in the center of distribution (kurtosis), and departure from symmetrical distribution (skewness). Pore water evidently represents saturated solutions, but in the identity and relative concentration of commoner anions it is quite similar to dilute spring and mine water. Applications to geophysical prospecting are discussed.

(2) Mahdi S. Hantush (University of Utah, Salt Lake City, Utah) and C. E. Jacob (Brigham Young University, Provo, Utah) Flow to an Eccentric Well in a Leaky Circular Aquifer--The solution is obtained for both steady and non-steady flow to a well eccentrically placed in a leaky circular aquifer. Two external boundary conditions are considered: constant head and zero flux. The well is idealized as a mathematical sink. The relationship between specific capacity and eccentricity is shown graphically for one set of parameters and compared with the same relationship for nonleaky aquifer.

(3) H. A. Waite and H. E. Thomas (U. S. Geological Survey, Salt Lake City, Utah) Effect of the Current Drought upon Water Supplies in Cedar City Valley, Utah--The ground water in the pumping district in Cedar City Valley, Utah, is considered to be fully appropriated, and the Utah State Engineer has not authorized drilling of irrigation wells there since 1942, except as replacements for wells having established rights. In spite of this regulation, the water levels in representative wells in 1953 were the lowest of record, and three to five feet lower than the minima recorded during the drought of the 1930's. This recession is attributed in large part to the current drought in the southwestern United States: In the five years ending October 1, 1953, precipitation at Cedar City was markedly less than in any other five-year period in the past 50 years, and stream runoff was likewise far below average. Ground-water withdrawal has exceeded replenishment in these drought years, but it cannot yet be concluded that the ground-water resources are over-developed in the sense that pumpage exceeds the long-term average replenishment to the reservoir.

(4) David K. Todd (University of California, Berkeley 4, Calif.) Unsteady Flow in Porous Media by Means of a Hele-Shaw Viscous Fluid Model--The problem of unsteady flow in porous media was investigated for the two-dimensional case by a model analogy, consisting essentially of an oil flowing through a narrow glass channel. The apparatus, known as a Hele-Shaw viscous fluid model, avoided the difficulties of measuring flow in porous media. The model was calibrated by steady flow measurements. Unsteady flows, composed of sudden releases of oil into and out of the channel, were recorded and analyzed. Results were presented in graphical form using dimensionless parameters. Agreement with numerical solutions of the basic non-linear differential equation, as applied to gas flow through porous media, was obtained. A study of a series of solitary sine waves was made as a model analogy of the damping of a flood hydrograph in a ground-water table adjacent to a stream. Results indicated that the damping rate was independent of both amplitude and period of the flood wave and that the damping distance was a function of the period but not of the amplitude.

(5) Boris J. Bermes (126 Ray Street, Bakersfield, Calif.) and C. E. Jacob (Brigham Young University, Provo, Utah) Further Correlation of Precipitation and Ground-Water Levels on Long Island, New York--This study is an extension of the work of Jacob in 1943 and makes use of ten additional years of data. An attempt is made to improve upon the correlation by using an exponential weighting function for the calculation of effective average precipitation and by the adjustment of the precipitation data through double-mass plotting. Ground-water levels are correlated statistically by the Doolittle method of multiple linear correlation with effective average precipitation expressed in two independent variables, one a function of the assumed exponential weighting curve, and the other a function of its corresponding harmonic. The highest correlation of 89 pct is six per cent higher than that obtained using Jacob's values of effective average precipitation. The apparent instability of the water table is discussed in the light of the theory of nonsteady flow in thin aquifers.

(6) R. L. Cushman and L. C. Halpenny (U. S. Geological Survey, Tucson, Ariz.) Effect of the Western Drought on the Water Resources of Safford Valley, Arizona, 1940-1952--Records of precipitation, runoff in the Gila River, ground-water withdrawals for irrigation, and changes in groundwater level in Safford Valley, Ariz., provide a basis for noting the effect of wet and dry periods on the hydrologic cycle. An unusually wet period, 1940-1941, was followed by a period of drought, 1942-1952. The irrigable area is limited by natural causes, the area irrigated with surface water is effectively limited by court decree, and less than 1000 acres is irrigated exclusively from wells. Thus relatively little expansion in this irrigated area has occurred during the period concerned, to obscure the climatic effects, although cultivation has been more intensive in recent years and

the water demand has been correspondingly larger. The wet period of above-normal stream flow and ground-water levels provided a cushion that delayed and reduced the effects of the drought. As the ground-water storage in the valley is relatively small, however, withdrawals of ground water as a supplemental supply for irrigation eventually lowered water levels sufficiently to reduce well yields. The concentration of dissolved mineral matter increased in the remaining ground water, making it less desirable for irrigation use than previously.

(7) George S. Benton and Jack Dominitz (Johns Hopkins University, Baltimore, Md.) The Use of Atmospheric Data in the Evaluation of Evapotranspiration--A method of evaluating evapotranspiration is developed which is based on the mass balance of water vapor in the atmosphere. The method is applied to various regions of the North American continent for the calendar year 1949 and the results obtained are compared with hydrologic data and with an empirical method of estimating evapotranspiration. It is shown that accurate values of evapotranspiration can be obtained for large areas such as the entire continent, but that the accuracy of the method is reduced as the size of the area under consideration is decreased. The potentialities and limitations of the proposed method are evaluated.

(8) Lawrence E. Nielsen (Monsanto Chemical Co., Springfield, Mass., and Field Leader of the Juneau Ice Field Research Project, American Geographical Society, 1953) Regimen and Movement of the Taku Glacier, Alaska--The theory of equilibrium glaciers is developed, and the interrelationships between the excess snow accumulation in the upper regions, the yearly ablation of bare ice below the firn line, the velocity of flow of ice, and the dimensions of a glacier are discussed. These concepts are then applied to the Taku Glacier. The results indicate the Taku is in an excellent state of health. The lower few miles of the glacier are in near equilibrium and check the predictions of the theory. The behavior of the central region of the Taku can be explained in two different ways: (1) The glacier is in equilibrium, but the thickness of the ice as measured by seismic methods is too small. (2) The glacier is not in equilibrium, but a series of ice waves is advancing down the Taku. Additional information is required to decide between these two conditions.

(9) D. B. Krinsley (U. S. Geological Survey, Washington 25, D. C.) Glacio-Marine Chronology in the Thule Area, Greenland--Radiocarbon analyses of samples collected in the Thule area of northwest Greenland make it possible to (1) date a glaciation in that area, and (2) place a maximum date on the development of raised marine terraces and on the disappearance of the glacier that occupied Wolstenholme Fjord north of Thule. A marine till was deposited more than 32,000 years ago (two radiocarbon dates) at Saunders Island ten miles west of Thule. This till was covered by beach deposits 8500 years ago (two radiocarbon dates) that were subsequently cut by younger marine terraces which are now as much as 130 ft above sea level. Wolstenholme Fjord, Thule, and the mouths of several of the valleys south of Thule had been cleared of ice by the time of the construction of the 75-ft marine terrace.

(10) Ernest H. Muller and Henry W. Coulter (U. S. Geological Survey, Washington 25, D. C.) Observations on the Knife Creek Glaciers, Katmai National Monument, Alaska--Several small glaciers at the head of Knife Creek in Katmai National Monument, Alaska, were beheaded by the 1912 eruption of Katmai Volcano and buried under a thick blanket of loose pumice. Nevertheless the glacier termini have been nearly stationary since 1912, according to detailed stratigraphic studies made near the ice margin. Below an elevation of 4000 ft the glaciers are covered with the 1912 pumice deposits and little downmelting takes place. Instead, permafrost has aggraded to within a few feet of the surface of the pumice mantle, rendering the glacier nearly static. By contrast, where the glaciers lack pumice cover, there is marked surface ablation, lowering the surface by 2/3 to 1 3/4 inches per day during the two-month interval from July to September, 1953.

(11) Walter T. Wilson (U. S. Weather Bureau, Washington 25, D. C.) Analysis of Winter Precipitation Observations in the Cooperative Snow Investigations--In the Cooperative Snow Investigations of the Corps of Engineers and the Weather Bureau, observations were made of precipitation in different kinds of gages and of water equivalent and change of water equivalent of snow on the ground at a great variety of station sites for the five winter seasons ending 1950-1951 in the mountains of California and Montana. Much of the variation in catch of precipitation over rugged areas of four to 20 sq mi is ascribed to variations in local exposure and in natural sheltering of the gages. Wind speed appears to be a good measure of the adequacy of gage shelter and of precipitation catch. The error in sampling of water equivalent for average snow courses is about the same order of magnitude as the maximum daily change in water equivalent. For seasons of several months' length, observations of gage catch and of accumulated snow on the ground, each at good sites, appear to have comparable precision though there are inherent limitations in the validity of such comparisons.

(12) Frank C. Allen, Robert E. Glover, Walter U. Garstka, and Howard M. Posz (U. S. Bureau of Reclamation, Denver, Colo.) Heated Precipitation-Gage Intake Tube--The design and functioning of a heated precipitation-gage intake tube is described, illustrated with drawings and photographs of an installation now in its third year of service in the field. Heat is transported to a specially constructed intake tube through a vapor-phase system using an evaporable liquid having a boiling point of about 40° F. The source of heat is combustion of liquified petroleum gas. The system provides sufficient heat to prevent adherence of snow and ice to a precipitation-gage intake tube, thus preventing the usual capping-over and incapacitation of gages operated under winter conditions. The system was invented as part of the development by the Bureau of Reclamation of an unattended radio reporting rain and snow gage network now in service in the Sacramento River basin, California.

(13) L. D. Love (Rocky Mountain Forest and Range Experiment Station, Ft. Collins, Colo.) The Effect of the Killing of Spruce and Pine by Bark Beetles on the Streamflow of White River, Colorado--The death of the Engelmann spruce and lodgepole pine killed by the spruce bark beetles on large areas of the White River drainage in western Colorado has been associated with increased streamflow of the White River. The White River has been gaged near Meeker, Colorado, since 1934; its drainage area is 762 sq mi. Total annual streamflow of the White River has been divided into three periods; namely, (1) the 1937-1940 water years before the killing of the spruce and pine; (2) the 1941-1946 water years during which successive stands of spruce and pine were killed; and (3) the 1947-1951 water years after the killing of the spruce and pine had been completed. After adjusting for climatic fluctuations, the analysis shows, when compared to the 1937-1940 water years, that the total annual streamflow on the average increased by 1.22 inches during the 1941-1946 water years and by 2.28 inches during the 1947-1951 water years. As indicated by the studies in lodgepole pine and spruce-fir forests at the Fraser Experimental Forest, it is not surprising that more water now passes the stream gage at Meeker, Colorado. The effects of the death of the spruce and lodgepole pine killed by the bark beetles on streamflow are similar to the effects of harvesting or thinning mature stands of timber; that of reducing snow interception.

(14) H. E. Brown (Rocky Mountain Forest and Range Experiment Station, Ft. Collins, Colo.) and E. G. Dunford (Pacific Northwest Forest and Range Experiment Station, Portland, Ore.) Streamflow in Relation to Extent of Snow Cover--An exploratory study was made in the snowmelt season of 1950 near Fraser, Colorado, to determine the relation between extent of snow cover and streamflow on St. Louis Creek. Snow cover was mapped by ocular estimates from observation points and intervals during the melting season. Indications were found of a close relationship between areal extent of snow cover and streamflow. This relationship may provide a new basis for accurate short-term forecasts of: (1) total streamflow during the snowmelt period, (2) date of peak flow, and (3) discharge at peak flow. The areal extent of remaining snow cover appeared to be more closely related to streamflow than was the volume of water remaining in the snow cover. The possibility of index surveys to evaluate snow cover in lieu of complete snow cover surveys should be considered in future studies.

(15) Ronald L. Ives (Cornell Aeronautical Laboratory, Buffalo, N. Y.) Past and Present Courses of the Sonoyta River--The Sonoyta River, an ephemeral stream rising in the mountains of south central Arizona and vanishing, under ordinary conditions, in a series of playas and inland deltas east of the Pinacate lava fields of Sonora, shows clear evidence of multiple interruptions of the arid-land erosion cycle. Studies in this area, incorporating not only personal field work, but also careful observations made over a span of years by Alberto Celaya and Ygnacio Quiroz; and historical references dating back to the work of Kino, Manje, and Salvatierra in the latter part of the seventeenth century, disclose that the upper course of the river, roughly from Agua Dulce east, has been fixed throughout much of the Pleistocene; but that the lower course has changed repeatedly. The original mouth was apparently at Pozo Caballo on the Gulf of California almost due west of Sonoyta. The channel to this mouth was obliterated by an early eruption of Pinacate Volcano. The present mouth is southeast of Puerto Penasco, Sonora, and is reached by only one of the many distributaries of the river below Batamote Hill. The course between Agua Dulce and Batamote has been modified in late prehistoric times by the most recent lava flows from craters parasitic to Pinacate Volcano. The problem of tracing the present and ancient courses of the river has been complicated by changes in rainfall and runoff pattern in the area, but the general conclusions reached have been strengthened by icthyological findings independent of the physiographic study.

(16) E. G. Dunford (Pacific Northwest Forest and Range Experiment Station, Portland, Ore.) Surface Runoff and Erosion as Affected by Precipitation Characteristics and Land Use in the Colorado Front Range--Surface runoff and erosion are increased by grazing on a bunchgrass site as well as by tree cutting and litter removal in a young ponderosa pine stand. In each of these two cover types, data are obtained from identical sets of six plots of 0.01 acre. Moderate and heavy grazing have caused surface runoff to increase by significant amounts and in proportion to intensity

of use. Erosion has measurably increased as a result of heavy grazing but only in negligible amounts on the moderately grazed plots. Removal of trees and litter cover from the young pine plots caused an immediate jump in surface runoff and erosion. Storm frequency, size, and intensity account for two-thirds or more of the variation in surface runoff from plots of a given cover type and treatment application.

(17) Elliott M. Flaxman and Robert L. Hobba (Soil Conservation Service, Portland, Ore.) Some Factors Affecting Rates of Sedimentation in the Columbia River Basin--Sedimentation surveys were made of 38 stockponds in the Columbia River Basin, Blue Mountain, and Payette-Snake River Plain sections of the Columbia River Basin. Related information on the contributing watersheds was also obtained. Multiple regression analyses of the available data were made in order to determine the effect of watershed characteristics and other major factors on stockpond sedimentation. The results show that five factors or variables account for 77 pct of the variation in sediment accumulation in the stockponds surveyed. These factors include the amount of land subject to accelerated erosion, the original pond storage capacity per square mile of watershed, age of pond, size of watershed, and amount of average annual precipitation. The effect of each variable on the annual rate of sedimentation if it were functioning independently is discussed, as well as limitations in use of the derived multiple regression equations.

(18) B. A. Bakhmeteff (late Professor of Columbia University) and N. V. Feodoroff (Manhattan College, New York, N. Y.) The Outflow through Slits--The slit experiments were intended primarily to disclose the eventual forms of transition between rapid and tranquil motion. The term "slit" is used to designate an opening in a bulkhead extending over the whole width of the channel and operating under a pressure conditioned by the headwater level. It was thought that the outflowing vein offers the simile of a weir nappe. The shape of vein and other flow parameters will obviously depend on whether or not the under nappe space is ventilated. From the experimental work set at Columbia University Fluid Mechanics Laboratory, the physical features of the outflowing vein were studied. The complexity of the slit outflowing pattern is of great interest to practicing engineers. Therefore, the outflow pattern from free to complete submergency was investigated. Also the overall relation of the geometrical framework was sought in the form of unit width discharge, $q = C_s d_s \sqrt{2g} \sqrt{H} = (C_s d_0/H) \sqrt{2g} H^{3/2}$ and in this way the discharge factor C_s was evaluated. The discharge also was related with the slit opening by way of dimensional parameter (similar to ground sluice) $\lambda = q^2/gd_s^3$ when λ is kineticity factor similar to Froude number. We considered outflow pattern two-dimensional. The arrangement was made to eliminate separation. The outcome of the experiments justified the anticipation. However, certain features of flow appeared to be of such particularly unexpected nature that complimentary phenomenological types had to be added to the heretofore accepted basic transition forms.

SECTION OF TECTONOPHYSICS

(1) John W. Harrington (Southern Methodist University, Dallas, Texas) Are Differences in Crustal Layering a Logical Basis for the Analysis of Orogeny?--Selected seismically determined crustal layerings show a marked relationship between the time of the last orogeny and the depth to the Mohorovicic discontinuity consistent with the Airy theory of isostacy. About 64 pct of the measurements placing the discontinuity below 40 km represent areas with Cenozoic orogenies, 14 more with Mesozoic orogenies. Of the measurements, 71 pct above 40 km represent areas with Precambrian or Paleozoic orogenies. If this is affirmation, implications of a cyclic mechanics from trough to wadded crust to uplifted and beveled shield are evident. Following this reasoning, an hypothesis which integrates the origin environments for Appalachian-type structures, sheared tectonites, massive crystallines, and multiple erosion surfaces during uplift is formulated. The importance of the basic premises is shown to depend largely on the certainty of seismological estimates.

(2) John S. Sumner (Department of Geology, University of Wisconsin, Madison, Wisc.) Consequences of a Polymorphic Transition at the Mohorovicic Discontinuity--As a working hypothesis, the lower crustal boundary (Mohorovicic discontinuity) is assumed to be a normal polymorphic transition. Seismic, gravitational, and thermal data are used to study the pressures, density contrasts, and temperatures involved in this concept. The differences in the depths of the Mohorovicic discontinuity under oceans and continents, respectively, are used to examine the properties of the polymorphic transition. If continental and oceanic thermal gradients are plotted as functions of temperature and pressure, they intercept the Mohorovicic discontinuity at seismically determined pressure levels. These continental and oceanic thermal intercepts define the temperature-pressure gradient of the presumed phase boundary. Conversely, true temperatures at the Mohorovicic discontinuity could be determined. The approximate heat of transformation is derived from Clapyron's equation. Consequences of the phase change can be correlated with the assumptions of isostasy and certain puzzling seismic and gravity anomalies.

(3) Wm. B. Farrington (University of Massachusetts, Amherst, Mass.) Analysis of Stress Conditions in the Upper Spraberry in Western Texas- Upper Spraberry cores were studied to learn whether fractures were open in the formation or only incipient. Release of fluid pressures in a pressure vessel into which core samples had been placed produced longitudinal axial fractures in previously unfractured cores showing that some of the fractures must be incipient. A statistical study of core diameters showed that the core diameter across fractures was slightly less than along the fractures. The difference in core diameters may have been the result of a small difference in the magnitude of the two principal horizontal stresses, which difference was computed by a knowledge of Young's modulus under formation conditions. The Mohr diagram was used to analyze the stresses in three dimensions, while the Mohr envelope indicating rupture conditions was constructed by data obtained from tension and compression tests on core samples. The tensile stress required to cause fracture as determined with the Mohr diagram compares favorably with the Hydrafrac pressure required for the "formation break." The average horizontal stress appears to be about half the vertical stress due to overburden, and this may be due in part to the low value of Poisson's ratio.

(4) J. Tuzo Wilson (University of Toronto, Toronto, Ontario, Canada) A Physical Explanation of Graben and Zwischengebirge--A. E. Scheidegger has recently shown that as a corrollary of his theory of arc formation either one or two additional fractures must spring from the junctions of arcs. In this paper it is shown that at junctions with one fracture this gives rise to a graben and juxtaposition of the primary and secondary arcs. The Appalachians provide several examples with grabens along the Saguenay River, Ottawa River, Rough Creek, and Nemaha uplift. Where two fractures form they are lineaments and the secondary arc is bounded by them and forced to form far from the primary arc. In the Cordillera the coast ranges of British Columbia, United States, and Lower California are primary arcs. The Rocky Mountains of United States and Canada are two secondary arcs bounded by the Texas, Wyoming, Montana, and Fraser lineaments and forced to form far inland across the mountain plateaux or zwischengebirgen. The theory incidentally explains why these two secondary arcs are at different distances from the coast mountains.

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Program for 1954
American Geophysical Union,
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TRANSACTIONS
AMERICAN GEOPHYSICAL UNION

Volume 35 June 1954 Number 3

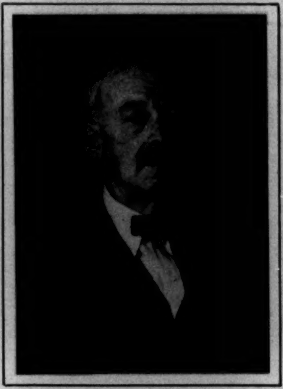
SIXTEENTH AWARD OF THE WILLIAM BOWIE MEDAL

CITATION

H.H. Hess

Mr. President, members and guests of the American Geophysical Union: I have known Richard Montgomery Field since 1926 - first as student, then as an assistant, and finally as a colleague. There is much I owe to him, and I am happy to be the one asked to present him to you this evening as the Sixteenth Recipient of the Bowie Medal.

Looking back at previous medalists, Gutenberg, Jeffreys, Sverdrup, Adams, Lambert, Macelwane, Meinesz, Daly, Bjerknes, Bigelow, Meinzer, Heck, Fleming, Day, and Bowie, I think it is fitting that Field's name should be the next on this list of truly great men in the development of geophysics in this country. He was President of the Union 15 years ago and perhaps did more to advance it as a vigorous scientific society than any man except John Fleming.



Richard Montgomery Field
Recipient, Sixteenth Award,
William Bowie Medal - May 4, 1954

Of all the medalists Field most closely resembles in attributes the first recipient, William Bowie. I do not know whether this is because Field inherently resembles Bowie, or whether Bowie, a close friend of his, strongly influenced him in his younger days. Perhaps both propositions are true in some degree.

The Bowie Medal is awarded for "cooperative research in fundamental geopnysics." Field's genius lies in the astute recognition of fruitful problems to attack, particularly where the development of a new technique or theory in one science could profitably be adapted to solving a major problem in another science. He was the first one in this country to appreciate fully the immense importance to geological theory of Vening Meinesz's gravity work at sea in the late 1920's.

Field rarely followed through with research work on his own on the magnificent problems he found, but with an equal astuteness and a keen judgment of men, he found some likely young fellow to put to work on the problem. He invariably found the financial, institutional, or governmental support to make possible and facilitate the carrying out of the research program. This whole procedure is, I think, what is meant by "cooperative research" and this is why he is eminently qualified to receive the Bowie Medal.

Perhaps the finest compliment one could pay to Field's judgment and endeavor is to note where some of these young men he found are today. To mention a few, there are Maurice Ewing at Columbia; "Ted" (now Sir Edward) Bullard, Director of the National Physical Laboratory in England; J. Tuzo Wilson of Toronto; George Woollard of Wisconsin, D. C. Skeels; and a good many others.

His early work on Ordovician limestones led to the study of lime muds in the Bahamas, thence to gravity at sea, and into geophysics. He organized and was Chairman of the Special Committee for Geophysical and Geological Study of Ocean Basins of the AGU. He also organized the Navy-Princeton and Navy-Geophysical Union gravity measuring expeditions in the West Indies. The list of committees and commissions of the AGU and IUGG of which he was chairman or an active member are too numerous to mention here.

In 1945 he suffered a serious accident which, but for a miracle of surgical skill, might have cost him his life. Many a man might have quietly retired after so serious a blow. But taking up life again in South Duxbury in 1951, he founded the American Institute of Geonomy and Natural Resources to carry forward some of those courageous ideas for which he was well known to so many of us.

Throughout his long career he has been ably and lovingly assisted by his wife Fanny Field. For cooperation in research she certainly deserves honorable mention on this occasion.

No scientist can be truly great and be devoid of a sense of humor. In this regard I might quote from a letter I got from Field a few days ago in which he expressed surprise that he was chosen to receive the medal and added, "This is the first medal that I have been awarded since 1905 when I won the 20-yard dash in three seconds."

It is a great pleasure, Mr. President, to present to you Richard Montgomery Field.

Presentation by President James B. Macelwane

Dr. Richard Montgomery Field, brilliant conceiver and courageous promoter of cooperative geophysical research, farseeing inspirer of oncoming geophysical talent, successful organizer of international projects, great President of the American Geophysical Union at a critical time in its history, the one man primarily responsible for the founding of the medal in honor of William Bowie, in honoring you today, sir, the American Geophysical Union honors itself. It is my happy privilege as President of the Union to represent the membership in conferring on you, sir, the Bowie Medal Award for 1954.

Response and Acceptance by Richard M. Field

Thank you President Macelwane! Thank you Dr. Hess: Thank you fellow geophysicists! Thank you everybody! All men have "Great Expectations" but I never expected that my name would be linked with our "Mutual Friend," William Bowie. This is for me, not only a great honor, but also a frightening responsibility. I worked hard for Bowie only because it was fun. His fun was the AGU and the IUGG so it naturally became my fun also. Bowie was a great leader because when he thought of a new game he got some one else to be captain of the team. And how he enjoyed doing it! He was one of the greatest bridge players in Washington because he made his partner feel as if he also was a great player. And when his partner overbid, and Bowie had to play the hand, he won it. Why? Just to prove that his partner was a clever partner!

Speaking of partners, Mrs. Field has asked me to say this for her. I quote: "I feel very proud and happy. I may be the first woman to be included in a citation accompanying the William Bowie Medal, and through my husband I would like to express humbly my deep appreciation to Dr. Hess."

In conclusion, I shall always consider that the 1954 award of the William Bowie Medal is to Fanny and Richard Field.

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GEOGRAPHICAL POSITIONS FROM STELLAR AZIMUTHS

C. H. Ney

Abstract--A method is developed whereby latitude, longitude, and azimuth are deduced simultaneously from azimuth observations on three or more stars. The method is particularly advantageous for high latitudes. A set of observation equations of the form $x(d\phi) + y(d\lambda) - (dA) + l = 0$ are solved by least squares for the best values of $(d\phi)$, $(d\lambda)$, and (dA), the corrections to assumed values of the latitude, longitude, and azimuth. Criteria for sharpness of determination are given. The discussion includes the choice and identification of stars and the computation of a numerical example. Using the most favorable selection of stars, and eliminating personal equation, geographical positions correct, astronomically, to about one-half a second of arc may be obtained by this method.

During the last twenty years, two methods have been employed by the Geodetic Survey of Canada for the astronomic determination of position. For Laplace azimuth work, the establishment of provincial boundary lines and the determination of deviations of the vertical, the astronomical telescope oriented in the meridian plane has been used exclusively. For the establishment of stations of second-order accuracy for mapping and charting in remote areas of the north, the astrolabe method applied to the precision-type theodolite has been employed.

The astrolabe method involves the observation of a number of stars at a fixed altitude in each quadrant of the horizon. To obtain the requisite precision of position determination, rapid changes of star altitude per unit of time are essential. Unfortunately, in polar and subpolar areas, the rate of change of altitude for any particular star is much less than in the more southerly temperate zone. Hence, it is apparent that the astrolabe method is not suitable for work in polar regions.

It is also widely recognized that altitudes cannot be measured with the same degree of precision as horizontal angles. One particularly unfavorable feature inherent to the use of the fixed altitude method is the difficulty of maintaining the theodolite telescope at a fixed vertical angle. For high latitude work, a method of geographical position determination based on the measurement of horizontal angles should, therefore, comprise certain factors of superiority over methods based on the measurement of altitudes.

The method herein proposed for the simultaneous determination of latitude, longitude, and azimuth offers a system based on the movement of stars in azimuth instead of in altitude. It involves the use of differential formulas analogous to those developed by Chauvenet for the determination of latitude, whereby corrections to assumed values of the altitude, latitude, and hour angle are derived from observed altitudes of three or more stars. Under certain conditions, the proposed method may prove of greater utility than the altitude method. Its use would permit the successful completion of an observational program in a remote area, where a damaged vertical-circle assembly of a theodolite could not be repaired or replaced. It promises great speed of position determination without the necessity of accurate instrument orientation, and without the preparation of an observing program. In addition, it permits observational work to be carried out when only small parts of the sky are free from clouds. In this respect, it is superior to most other methods.

Generalization of method--As a preliminary step to the observational work, an azimuth reference line is selected on the ground and marked by a suitable target one or two miles distant from the observation station. From an observation on the Sun or a star, or from readings of the magnetic compass, an approximate azimuth A_A of the line is assumed. Approximate numerical values ϕ_A and λ_A of the latitude and longitude of the observation station are also assumed. From three independent determinations of the azimuth of the reference line made from three different stars, the corrections $d\phi$, $d\lambda$, and dA to the assumed values of the latitude, longitude, and azimuth are derived algebraically by the use of differential formulas. For a solution of greater accuracy, a series of observations on each of the three selected stars, or observations on a dozen or more different stars, are combined in a least-squares solution.

The data used for the calculation of the stars' azimuths Z are the assumed latitude ϕ_A, the local sidereal time derived from the differences between Greenwich Sidereal Time and the assumed longitude λ_A, and the stars' declinations. Where the star observations are restricted to "Fundamental Stars," the errors in declination may be assumed to be negligible.

Development of differential formulas--By a differentiation of the fundamental spherical trigonometric formula

$$\sin B \cot A = \sin c \cot a - \cos c \cos B \qquad (1)$$

where A, B, and c are allowed to vary, there may be derived the differential formula

$$dA = -(\sin A \cos C/\sin B)\, dB - (\sin A \cos b/\sin b)\, dc \qquad (2)$$

For the astronomical triangle PZS, where P the pole, Z the zenith, and S the star replace B, A, and C of the spherical triangle, and where $dc = -d\phi$, and $d\tau = -d\lambda$

$$dZ = (15 \sin Z \cos S/\sin \tau)\, d\lambda + (\sin Z/\tan \zeta)\, d\phi \qquad (3)$$

where Z is the azimuth, τ the hour angle, S the parallactic angle, ζ the zenith distance, δ the declination, ϕ the latitude, λ the longitude, and where dZ and $d\phi$ are in seconds of arc, and $d\lambda$ in seconds of time.

Eq. (3), which may be found in a slightly different form in Volume I of Chauvenet's Spherical and Practical Astronomy, gives the change dZ in the computed azimuth due to the small differences $d\lambda$ and $d\phi$ between the assumed and true longitudes, and the assumed and true latitudes respectively.

The coefficients $(15 \sin Z \cos S)/(\sin \tau)$ and $(\sin Z)/(\tan \zeta)$ may be determined with the aid of graphs. First, calculate the azimuth for each star pointing, and the parallactic angle and zenith distance for the first and last pointing of a series. The values of the cosine of the parallactic angle and the tangent of the zenith distance may then be taken by inspection from a graph constructed to show the rates of change in $\cos S$ and $\tan \zeta$. For a series of observations over a relatively short time, the curves may be assumed to be linear.

The azimuth Z of the star should be computed from the hour angle formula

$$\tan Z = -(\cot \delta \sec \phi \sin \tau)/(1 - \cot \delta \tan \phi \cos \tau) \qquad (4)$$

For close circumpolars, Table 13 of U. S. Coast and Geodetic Survey Special Publication 237 is helpful.

The parallactic angle S may be deduced from the formula

$$\sin S = \cos \phi \sin Z/\cos \delta \qquad (5)$$

The zenith distance may be derived from readings of the vertical circle of the theodolite. However, it is probably more convenient to deduce it from the formula

$$\sin \zeta = \cos \delta \sin \tau/\sin Z \qquad (6)$$

In Figure 1, let A_0 the observed azimuth of the reference line AB be equal to the sum of A_A the assumed azimuth, plus the unknown correction dA to be derived in the reduction of the observations.

Also from the observation on the star S, the observed azimuth of the line is equal to Z the computed azimuth of the star, plus dZ the differential change due to the errors $d\lambda$ and $d\phi$ in the assumed longitude and latitude of the observation station A, plus M the angle measured clockwise from the star to the reference line.

In algebraic form, we have then the two equations

$$A_0 = A_A + dA \qquad (7)$$

$$A_0 = Z + (15 \cos S \sin Z/\sin \tau)\, d\lambda + (\sin Z/\tan \zeta)\, d\phi + M \qquad (8)$$

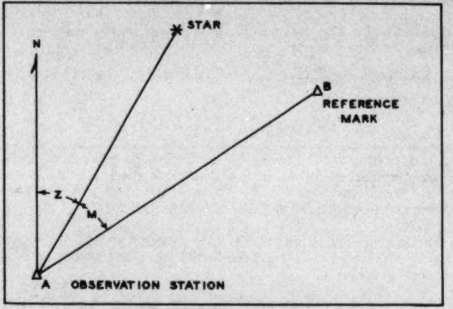

Fig. 1--Measured and computed horizontal angles

Equating (7) and (8), and rearranging, we derive

$$(\sin Z/\tan \zeta)\, d\phi + (15 \cos S \sin Z/\sin \tau)\, d\lambda - dA + (Z + M - A_A) = 0 \quad \ldots\ldots\ldots (9)$$

Conventions--In the measurement of hour angle, azimuth, and parallactic angle, the following conventions must be kept in mind.

The hour angle τ is measured from the local meridian westerly from zero to 360°.

Azimuth is measured from the north clockwise from zero to 360°. The signs of the coefficients $(\sin Z)/(\tan \zeta)$ and $(15 \cos S \sin Z)/(\sin \tau)$ are usually governed by the signs of $\sin Z$ and $\sin \tau$. However, for close circumpolar stars, the parallactic angle S may be greater than 90° in which case $\cos S$ is a negative quantity.

After the observation of three or more suitably chosen stars, the unknowns $d\phi$, $d\lambda$, and dA are determined from the solution of a corresponding number of observation equations conforming to the pattern of (9).

The observed values of the desired coordinates and azimuth are found by adding the derived corrections to the assumed values. Hence we have

$$\phi_0 = \phi_A + d\phi \qquad \lambda_0 = \lambda_A + d\lambda \qquad A_0 = A_A + dA \quad \ldots\ldots\ldots\ldots (10)$$

Selection of stars for sharp solution--The sharpness of the least-squares solution of the observation equations and the accuracy of the final results depend, in large measure, on the suitable choice of stars selected for observation. Where only three stars are observed, they should be so chosen that one of them influences strongly the determination of the latitude, one the longitude, and one the azimuth.

To select a star which will strongly influence the determination of the longitude, it is necessary to know under what conditions the coefficient of $d\tau$ in (3) becomes numerically large.

From (3)

$$dZ = -(\sin Z \cos S/\sin \tau)\, 15\, d\tau$$

But

$$\sin Z = \sin S \cos \delta/\cos \phi$$

$$\sin \tau = \sin S \sin \zeta/\cos \phi$$

Substituting these values of $\sin Z$ and $\sin \tau$ in (3), there results

$$dZ = (\cos S \cos \delta/\sin \zeta)\, 15\, d\tau$$

For dZ a maximum, both S and ζ must be equal to zero. This occurs when the star is in the meridian and in the zenith. Obviously, it would be impossible to make observations for azimuth when such conditions obtained. The best compromise would be the selection of a southern star within 20 or 30° of the meridian and between 40 and 60° in altitude.

For the special case where the star is observed in the meridian, the parallactic angle becomes zero and

$$dZ = (\cos \delta/\sin \zeta)\ 15\ d\tau = (1/A)\ 15\ d\tau$$

where A is the azimuth coefficient in the observation equation used in the determination of the clock correction in precise astronomical work by means of the astronomical telescope oriented in the meridian plane. Tabulated values of A, for varying values of δ and ζ as arguments, may be found in U. S. Coast and Geodetic Survey Special Publication 237.

Table 1 gives the approximate values of 15/A for varying values of declination and zenith distance. To select a star which will have a preponderant influence on the determination of the latitude, we again consider (3), where

$$dZ = (\sin Z/\tan \zeta)\ d\phi$$

Table 1--Values of 15/A

ζ	δ			
	0°	10°	15°	20°
°				
30	30.00	29.40	28.95	28.20
35	26.25	25.95	25.35	24.60
40	23.40	23.10	22.35	22.05
45	21.15	20.85	20.55	19.95

Table 2--Coefficient sin Z/tan ζ

ζ	Z			
	90°	80° 100	70° 110	60° 120
°				
30	1.7	1.7	1.6	1.5
40	1.2	1.1	1.1	1.0
45	1.0	1.0	0.9	0.9
50	0.8	...	...	...

In this case, the coefficient sin Z/tan ζ will have a maximum value when Z equals 90 or 270° and when ζ is zero. Here again, azimuth observations would be impossible for a star in the zenith. As the best compromise, a star should be selected which is within 10 or 20° of the prime vertical and between 40 and 60° in elevation. Table 2 shows approximate values of the coefficient for varying values of the azimuth and zenith distance. For a sharp determination of azimuth, a circumpolar star should be observed near elongation. However, in actual practice the choice of any circumpolar star at any hour will give good results.

The identification of stars--The utilization of the azimuth method of position determination necessitates the recognition or easy identification of the stars observed. Most experienced observers are able to recognize the first magnitude stars by sight. As these are the celestial bodies most useful for observation, no difficulty should ensue, except where observations are made through holes in the clouds. As a precautionary measure, it is advisable to read a vertical angle on each star at the time of the first pointing in azimuth. This will obviate any uncertainty of identification when the mathematical reduction is begun.

Knowing the approximate latitude, longitude, altitude, azimuth, and local sidereal time, an unknown star may be easily identified in three or four minutes by having recourse to the following method.

From (6) we have the relationship

$$\cos \delta \sin \tau = \sin \zeta \sin Z \qquad \text{or} \qquad \sin \tau = \sin \zeta \sin Z/\cos \delta \ .\ .\ .\ .\ .\ (11)$$

From simultaneously observed values of ζ and Z, the values of sin ζ sin Z may be computed. Next, an approximation of the star's polar distance is made by noting the star's position in the sky with respect to the pole star.

A more accurate approximation of the polar distance can be made by actual measurement on a cardboard protractor which can be constructed in a few minutes. To secure maximum accuracy in its use, nail a board to the stump of a tree (Fig. 2) so that the upper edge is pointing towards

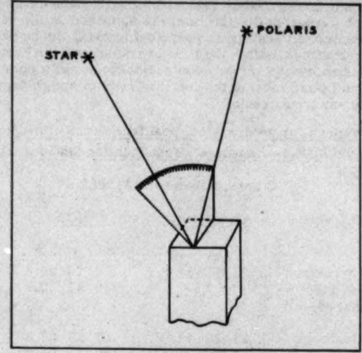

Fig. 2--Star identification

Polaris. Place one edge of the cardboard protractor along the edge of the board; rotate the cardboard about this line till the plane of the protractor intersects the star chosen for observation. In this position the protractor lies in the plane defined by the selected star, Polaris and the observer. The polar distance can then be read directly from the graduations.

In carrying out this procedure, it is assumed that Polaris is at the North Pole. The error in the measured polar distance due to the lack of coincidence of Polaris and the Pole will have a maximum value of plus or minus one degree. A correction to the measured value, which may be estimated mentally, may be applied if the added accuracy is required.

The value of τ having been computed from (11), the star's right ascension is derived from the relationship

$$\alpha = \theta - \tau$$

By consulting the publication Apparent Places of Fundamental Stars, the observed star may be identified at once by referring to the tabulated values of the right ascensions and declinations.

Numerical example--To demonstrate the feasibility of the method, a short observational program was carried out on November 13, 1952, at Standards Triangulation Station near the Geodetic Survey Building in Ottawa. High precision work was not attempted as the object of the experiment was to show the feasibility of the method. Due to smoke and water vapor in the atmosphere, only five bright stars were observed, some in very unfavorable positions too close to the horizon. As no reflecting prism was available for use with the instrument, pointings could not be made where the altitude exceeded 45° without introducing an unwarranted amount of physical discomfort.

A 5 1/2-inch precision-type Wild theodolite, which has no striding level, was used for making the star observations. To minimize the effect of errors in the observed azimuths arising from unknown inclinations of the horizontal axis of the telescope, a special observing technique was used. On several occasions, this system has proved to be of great value in making azimuth determinations with instruments which are not equipped with striding levels.

After levelling the instrument, the telescope is pointed at the star and the image brought into the field of view. The instrument is then clamped in position so that the moving image will cross the vertical wire of the reticule in one or two minutes. The horizontal plate level is then inspected for any error in centering. Any deviation from the exact center is corrected by a slight movement of the foot screws. The instant of star transit is recorded electrically on a chronograph by depressing a telegraph key when the star intersects the vertical wire. The horizontal circle is then read and recorded. Next, the instrument is turned clockwise and a pointing made on the reference object which usually is located close to the plane of the horizon.

After reversing the instrument, another rough pointing is made on the star as before and the instrument clamped in such a position that the image is approaching the vertical wire. Before the transit takes place, the foot screws are again readjusted to bring the horizontal plate level bubble to the center of the vial graduations. After the time of transit and the horizontal circle reading (HCR) are recorded, the instrument is turned counterclockwise and a pointing made on the reference object. If the horizontal plate level of the instrument is of a high degree of sensitivity, this technique will give remarkably good results.

Observations for geographical position from Stellar Azimuths

Station - Standards Triangulation Station

Ottawa, November 13, 1953

	Object	Chron. time	HCR	Elevation (measured)
		h m s	° ′ ″	° ′
Star 3	Formalhaut	23 17 54.0	185 10 25.2	14 36
	RO (reference object)		150 41 10.2	
Star 2	Aldebaran	23 26 40.5	87 33 07.8	20 56
	RO		150 41 04.9	
Star 1	Polaris	0 11 22.0	0 36 22.2	46 15
	RO		150 41 45.7	
Star 5	B Ursae Min.	0 04 05.0	347 41 34.0	32 58
	RO		150 41 42.7	
Star 4	Altair	23 53 45.7	255 08 52.5	26 09
	RO		150 41 29.0	

Mean value of clock correction $+ 14^{s}.20$

Reduction of observations--In the mathematical reduction of the observations, the following assumed values were used

$\phi_A = 45° 23' 30''$
$\lambda_A = 75 \ 42 \ 45 \quad (5^h \ 02^m \ 51^s.0)$
$A_A = 150 \ 40 \ 10$

The computations of the azimuths, the parallactic angles, and the coefficients of $d\phi$ and $d\lambda$ are not shown in detail. The resulting values, however, are given in Table 3.

Table 3--Tabulation of data for the formation of observation equations

Star	τ	Z	M	(Z+M-A)	S	ζ	$d\phi$ Coeff.	$d\lambda$ Coeff.
	° ′ ″	° ′ ″	° ′ ″	″	° ′	° ′		
1	334 59 25.5	0 34 56.8	150 05 23.5	+ 10.3	154 34	43 45	+ 0.010	+ 0.326
2	283 24 58.5	87 32 30.7	63 07 57.1	+ 17.8	47 00	69 04	+ 0.382	- 10.506
3	5 45 57.0	185 09 49.3	325 30 45.0	+ 24.3	4 11	75 24	- 0.023	- 13.401
4	61 22 45.0	255 08 01.5	255 32 36.5	+ 28.0	43 22	63 51	- 0.481	- 12.033
5	138 23 27.0	347 40 16.4	163 00 08.7	+ 15.1	33 45	57 02	- 0.138	- 4.010

The following observation equations may be written down at once from the data given in Table 3

1 Polaris $+ 0.010\, d\phi + 0.326\, d\lambda - dA + 10.3 = 0$
2 Aldebaran $+ 0.382\, d\phi - 10.506\, d\lambda - dA + 17.8 = 0$
3 Formalhaut $- 0.023\, d\phi - 13.401\, d\lambda - dA + 24.3 = 0$
4 Altair $- 0.481\, d\phi - 12.033\, d\lambda - dA + 28.0 = 0$
5 B Ursae Minoris $- 0.138\, d\phi - 4.010\, d\lambda - dA + 15.1 = 0$

In making the least-squares reduction, the first step is the formation of the normal equations as follows, with a check column on the right-hand side:

$d\phi$	$d\lambda$	dA	Absolute term	Sum
+ 0.3970	+ 2.6394	+ 0.2500	- 9.2081	- 5.9217
. . . . . .	+ 450.9423	+ 39.6240	- 909.7683	- 413.5626
. . . . . .	. . . .	+ 5.0000	- 95.5000	- 50.6260

A solution of the normals gives the following values of the corrections and their probable errors:

$$d\phi = +9''.7 \pm 0''.8 \qquad d\lambda = +1^{s}.048 \pm 0^{s}.041 \qquad dA = +10''.3 \pm 0''.4$$

By adding the derived corrections to the assumed values of the latitude, longitude, and azimuth, the observed values are obtained.

	Latitude	Longitude	Azimuth
Assumed value	45° 23′ 30.0″	$5^{h}\ 02^{m}\ 51^{s}.0$	150° 40′ 10″.0
Correction	+ 9.7	+ 1.05	+ 10.3
Observed value	45 23 39.7	5 02 52.05 75° 43′ 00″.7	150 40 20.3

The corresponding astronomic values from precise observations made at the same station are

$$\phi = 45^{\circ}\ 23'\ 40''.3 \qquad \lambda = 75^{\circ}\ 42'\ 56''.7 \qquad A = 150^{\circ}\ 40'\ 21''.6$$

The differences between the observed latitude and longitude and the values previously derived for the same station from precise observations are equivalent to 60 ft in latitude and 286 ft in longitude.

It is desirable to emphasize the fact that most of the stars chosen for observation in the illustrative example are at too low an altitude. Consequently, the coefficients of $d\phi$ and $d\lambda$ have values numerically unsuitable for obtaining results of a high degree of accuracy. By observing 15 or 20 stars at suitable positions in the sky, by using an instrument equipped with a striding level, and by ensuring the correct registration of the times of star pointings by using an electric chronograph, it is expected that geographical positions correct, astronomically, to about one-half second of arc, could be obtained.

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PROCEDURES USED TO IMPROVE THE QUALITY OF IONOSPHERIC DATA

Sanford C. Gladden

Abstract--The paper outlines procedures used in the examination of data received from 21 field stations. Figures are provided to illustrate the type of records examined and the results of interstation comparison. Stations separated by not more than four degrees of geomagnetic latitude are compared graphically as regards monthly medians of the various characteristics. Discoveries of operating errors which had escaped observation for several months are described. A type of scaling error discovered by graphical comparison of stations is mentioned.

The Ionospheric Data Quality Control Group of the Upper Atmosphere Research Section, Central Radio Propagation Laboratory, has as its primary function the examination of data received from 21 field stations including associated laboratories. These data comprise ionospheric soundings from equatorial, low latitude, and high latitude locations, and include a wide variety of records.

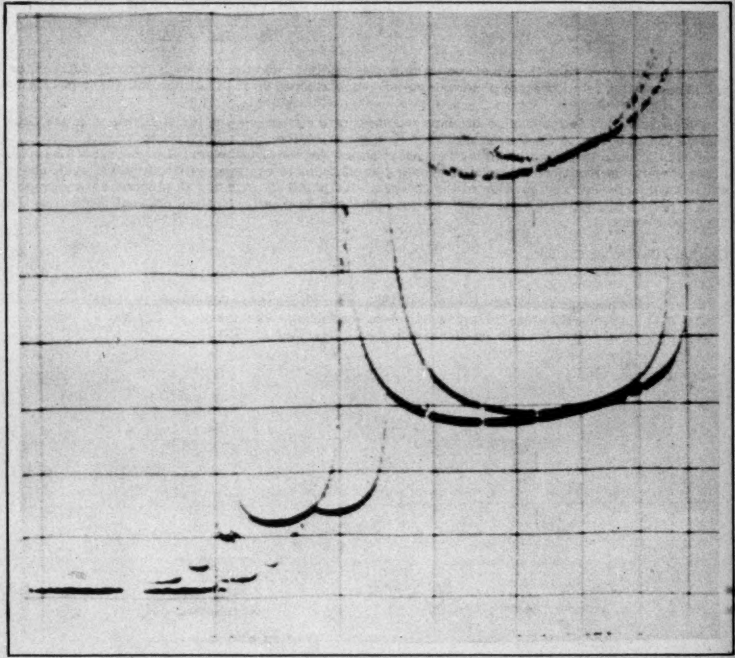


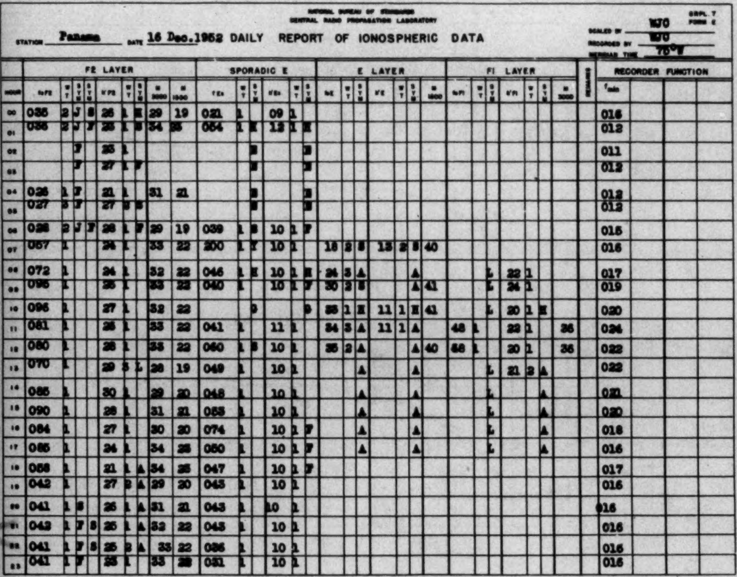
Fig. 1--Ionospheric record from Maui, T. H., for June 13, 1952, at 16h 03m, 150° W time

The examination helps to determine whether the stations submitting the data have scaled the records properly, and may assist the station engineer in uncovering operating errors.

The Type C-2 and C-3 automatic ionosphere recorders developed by the Central Radio Propagation Laboratory usually make ionospheric soundings at intervals of 15 minutes, supplemented by auxiliary probings at one minute before or after the hour. Vertically incident pulses varying in frequency from 1.0 to 25.0 mc are emitted, an interval of 15 or 30 seconds usually being required to perform one frequency sweep. The return echoes from the ionosphere are recorded photographically on 35-mm film. Imprinted on each record are frequency markers and height markers. The frequency markers are logarithmically spaced, while the height markers are linearly spaced, usually at 100 km intervals from 0 to 1000 km. The same spacing of markers is maintained for all equipment. Provision is made for other frequency sweep times and for other height marker intervals, as special conditions may require. At the high-frequency end of the record a line of automatically printed data indicates the station designation and the year, month, day, and minute.

Figure 1 illustrates the appearance of a single record obtained by the ionospheric station at Maui, T. H., on June 13, 1952, at 16h 03m, 150°W time. This record is considered somewhat unusual, in that traces for all regular layers are present for both the ordinary and extraordinary components.

For scaling, the film records are projected on a ground-glass screen, using magnification such as to bring them to the same size (approximately 16 by 31 cm) for all stations, so that a standard scaling grid may be used. In addition to height and frequency, the MUF-factor curves for 3000 and 1500 km are indicated on the grid.



NATIONAL BUREAU OF STANDARDS
CENTRAL RADIO PROPAGATION LABORATORY
CRPL 7
FORM E

STATION Panama DATE 16 Dec. 1952 DAILY REPORT OF IONOSPHERIC DATA

SCALED BY WJO
RECORDED BY WJO
MERIDIAN TIME 75°W

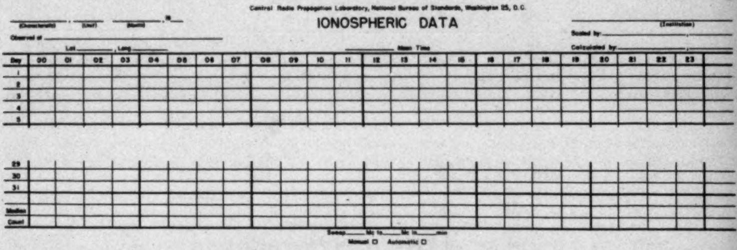
	F2 LAYER									SPORADIC E						E LAYER							F1 LAYER							REMARKS	RECORDER FUNCTION			
HOUR	foF2	W T	S Y M	S Y M	h'F2	W T	S Y M	M 3000	M 1500	fEs	W T	S Y M	h'Es	W T	S Y M	foE	W T	S Y M	h'E	W T	S Y M	M 1500	foF1	W T	S Y M	h'F1	W T	S Y M	M 3000		fmin			
00	035	2	J	S	26	1	E	29	19	021	1		09	1																	016			
01	035	2	J	F	25	1	S	34	25	054	1	K	13	1	K																012			
02			F		25	1						B			B																011			
03			F		27	1	F					B			B																012			
04	026	1	F		21	1		31	21			B			B																012			
05	027	3	F		27	3	S					B			B																012			
06	026	2	J	F	26	1	F	29	19	039	1	S	10	1	F																015			
07	057	1			24	1		33	22	200	1	Y	10	1		18	2	S	13	2	S	40									016			
08	072	1			24	1		32	22	046	1	K	10	1	H	24	3	A			A				L	22	1				017			
09	095	1			25	1		33	22	040	1		10	1	F	30	2	S			A	41			L	24	1				019			
10	096	1			27	1		32	22			B			B	35	1	H	11	1	H	41			L	20	1	H			020			
11	081	1			26	1		33	22	041	1		11	1		34	3	A	11	1	A		48	1		22	1		36		024			
12	080	1			26	1		33	22	060	1	S	10	1		35	2	A			A	40	56	1		20	1		36		022			
13	070	1			29	3	L	26	19	049	1		10	1				A			A				L	21	2	A			022			
14	085	1			30	1		29	20	048	1		10	1				A			A				L			A			021			
15	090	1			28	1		31	21	055	1		10	1				A			A				L			A			020			
16	084	1			27	1		30	20	074	1		10	1	F			A			A				L			A			018			
17	085	1			24	1		34	25	050	1		10	1	F			A			A				L			A			016			
18	058	1			21	1	A	34	25	047	1		10	1	F																017			
19	042	1			27	2	A	29	20	045	1		10	1																	016			
20	041	1	S		26	1	A	31	21	043	1		10	1																	016			
21	042	1	F	S	26	1	A	32	22	045	1		10	1																	016			
22	041	1	F	S	25	2	A	33	22	036	1		10	1																	016			
23	041	1	F		25	1		33	25	031	1		10	1																	016			

Fig. 2--Daily report form for ionospheric data

Data for the records made on the hour are the ones customarily scaled. Under conditions which do not permit the interpretation of the hourly record, or a record within five minutes of the hour, a value may be estimated by interpolating between preceding and following records separated by not more than two hours.

The scaled data are entered on daily record sheets, as shown in Figure 2. This form was designed to facilitate the entry of the data on punch cards. For that reason, frequencies are listed in tenth-megacycles and virtual heights in units of tens of kilometers.

In order to facilitate the computation of monthly median values and the use of the data in research, monthly tabulation sheets are prepared for the various characteristics, using the form shown in Figure 3.



Central Radio Propagation Laboratory, National Bureau of Standards, Washington 25, D.C.

IONOSPHERIC DATA

_______ (Characteristic), _____ (Unit) _______ (Month), 19__

Observed at ____________

Lat ______, Long ______

______ Mean Time

______ (Institution)

Scaled by: ______, ______

Calculated by: ______, ______

Day	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
1																									
2																									
3																									
4																									
5																									
29																									
30																									
31																									
Median																									
Count																									

Sweep ______ Mc to ______ Mc in ______ min

Manual ☐ Automatic ☐

Fig. 3--Monthly tabulation sheet for ionospheric data

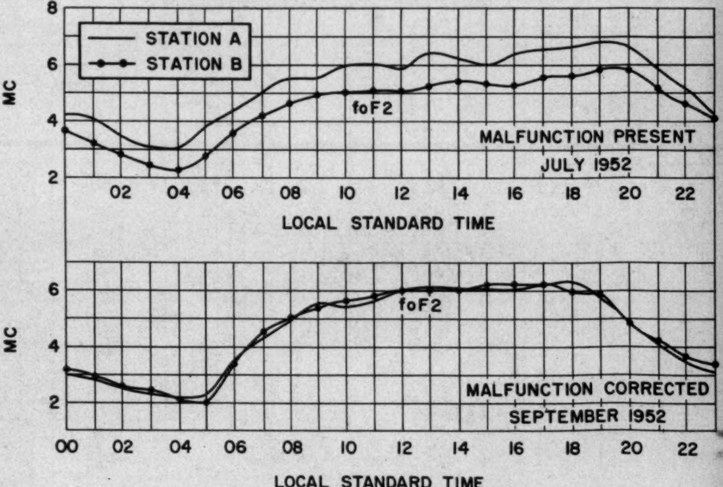


Fig. 4--Comparison of Stations A and B with and without malfunction

Upon receipt of the data and records, a spot check of scaling for three randomly selected days is made for a given station. The records for those days are completely rescaled. If serious errors involving one or more characteristics are revealed by this spot check, the films involved are rescaled for the entire month. Incorrect usage or interpretation of symbols is also noted. After such a check, the particular station's personnel are advised of the departures from accepted procedure, and if necessary, tracings of appropriate records are transmitted to clarify doubtful points.

Occasionally, the film records may not be received simultaneously with the data. On the basis of past performance of the station, and because of favorable comparison with check stations, the data may be provisionally released for use before the spot check is made. If the past examination of the records from the station or the comparison with check stations indicates questionable reliability of the data, release of the material is usually delayed pending arrival and examination of the records.

A number of equipment malfunctions stand out on the records, including compression or expansion of the height markers, short or long records, and faulty voltage regulation.

In order to detect other sorts of equipment malfunction, stations separated by not more than four degrees of geomagnetic latitude are compared in pairs and, when possible, in triads, as to monthly median values of the virtual heights, critical frequencies, and MUF-factors. The times reported by the individual stations are not reduced to local mean time.

Figure 4 illustrates one type of technical error so discovered. For simplicity, only foF2 values are shown. Station A, a training station of another agency, situated approximately one degree higher in geomagnetic latitude than Station B, appeared to have an error in the reported frequency value. Using Station B as a standard for comparison, a difference of approximately one megacycle for all values of critical frequency was discovered. Examination of the equipment showed that there had been a shift of frequency reference point by one megacycle, so that when the records were scaled using the standard overlay, the observers assigned an incorrect value to each point on the record. After correction of the equipment malfunction responsible, the two stations compared much better, as the lower of the figures indicates. Of course, exact agreement is not to be expected.

Figure 5 illustrates another type of equipment malfunction that is not revealed by ordinary equipment checks. Here we have a comparison of h'F2 and foF2 for Stations C and D, differing

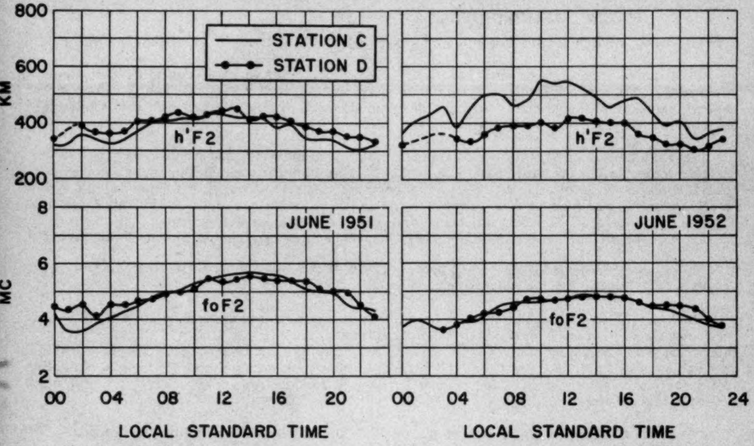
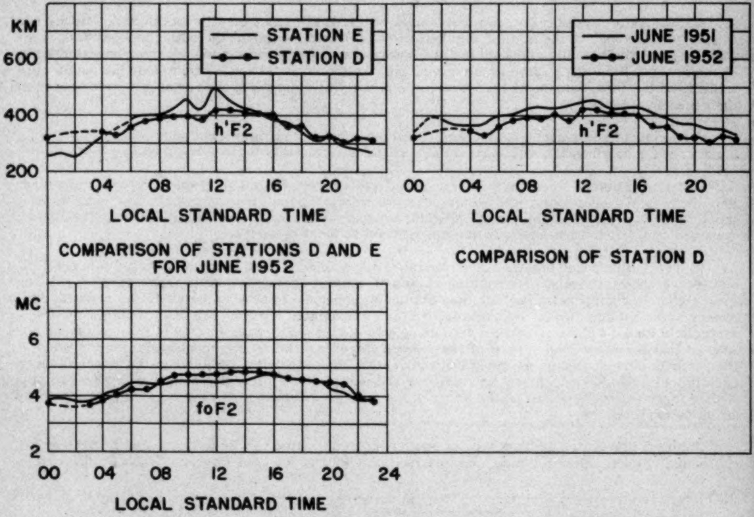


Fig. 5--Comparison of Stations C and D with presence of discrepancy in virtual height one degree in geomagnetic latitude, for June, 1951, and June, 1952. The values of foF2 agree well in the two cases, but the virtual heights differ considerably for 1952. In order to be certain that the check Station D was not itself in error, a comparison was made with a third station, E, two degrees lower geomagnetically than Station D, and also between h'F2 for Station D for June, 1951, and June, 1952 (Fig. 6).



COMPARISON OF STATIONS D AND E FOR JUNE 1952

COMPARISON OF STATION D

Fig. 6--Comparison (a) between Stations D and E for June, 1952; (b) of Station D with itself

The checks made of data from Station C for several months in 1952, rescaling being performed by different individuals, did not disclose any equipment discrepancy. Aside from occasional instances of compression or expansion, the standard overlay aligned well with the height markers on the record.

An examination of monthly tabulations from Station C indicated that a marked change in virtual heights took place in the latter part of June, 1951. This information, together with a series of comparison graphs, was forwarded to the station engineer. After a thorough equipment check by the station chief, it was found that an error of some 15 pct in the values of virtual heights from this station had existed for 18 months because of an incorrect equipment adjustment. After correction of this adjustment, the agreement of Stations C and D became much better, as shown in Figure 7.

In passing, it should be mentioned that the CRPL-F Series carries notes regarding errors in previously published data as they are discovered.

Station intercomparison serves not only to reveal equipment malfunctions but also to indicate scaling errors. Figure 8 shows that Station G agreed quite well with Station H, three degrees higher in geomagnetic latitude, both as regards h'F2 and foF2, but that it differed considerably in the values of (M3000) F2. The check of the records indicated that an incorrect method of scaling MUF-factors was being used. Station intercomparison revealed this scaling error prior to spot-checking the station.

Aside from the intercomparison of station data, the values at each station are compared with the corresponding monthly median values of the previous year. Figure 9 illustrates this type of comparison.

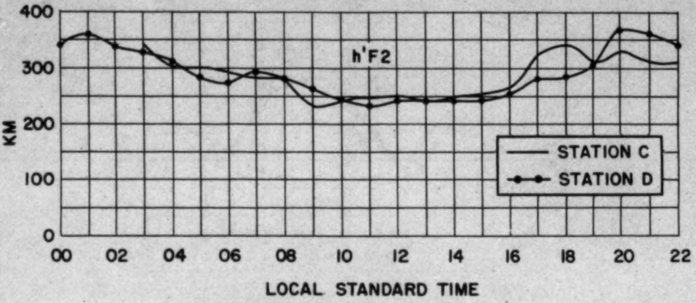


Fig. 7--Comparison of Stations C and D for December, 1952, after height discrepancy was corrected

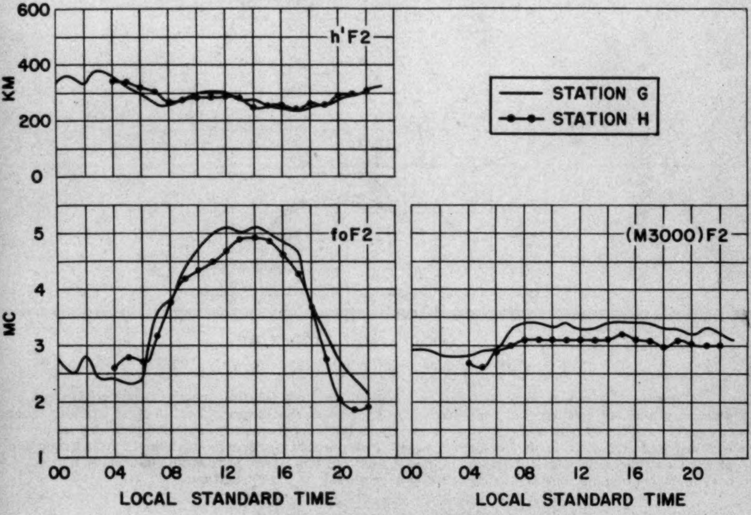


Fig. 8--Comparison between Stations G and H illustrating an error in scaling MUF-factors

In order to arrive at a satisfactory interpretation of the records, close study of preceding and following records is necessary. In a number of cases, it has been found profitable to make tracings of pertinent parts of consecutive records, thus minimizing the distracting effect of extraneous detail.

A considerable number of stations other than those examined by the present group transmit data to the Regular Propagation Services Section of the Central Radio Propagation Laboratory. These data are checked by a somewhat different system of intercomparison.

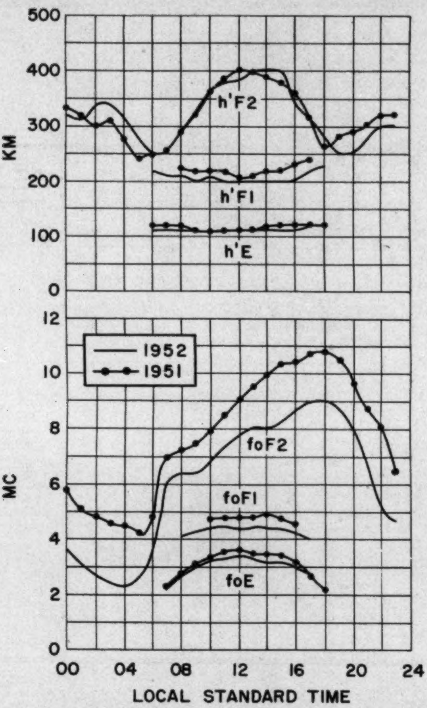


Fig. 9--Station comparison for July, 1951, and July, 1952

While the primary responsibility of the Ionospheric Data Quality Control Group concerns the stations regularly sending data and records to it, assistance has been given to other stations, even though the records furnished may differ considerably in appearance from those provided by the C-2 and C-3 automatic ionosphere recorders. The ionosphere records examined by the group are of such a varied nature that it is possible in the majority of cases to furnish reasonably satisfactory answers to questions regarding scaling procedures or interpretation.

National Bureau of Standards,
Washington 25, D. C.

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A METHOD OF ESTIMATING PRECIPITATION NORMALS FOR SHORT-RECORD STATIONS

James C. Coffin

Abstract--Regression formulas are developed from which estimates of the monthly normal precipitation at a station having a short record can be obtained. Using stations in western Washington the method is illustrated for records of ten years, five years, and one year in length. The error decreases as the length of record increases and the amount of error can be estimated. The computation of a single regression of 32-year means on ten-year means involving 30 stations permits the estimation of normals for all stations in western Washington having only ten years of record.

Introduction--During the planning phase of a cloud-seeding project, it was found that for purposes of analysis it would be necessary to have monthly normals for all existing precipitation stations in western Washington. In Weather Glossary [THIESSEN, 1945], a normal is defined in part as follows: "The average value which, in the course of years, any meteorological element is found to have on a specified date or during a specified month or other portion of the year, or during the year as a whole. . . ." and further, "The normal serves as a standard with which values occurring in a particular year may be compared." This is the exact purpose of the normals for this project. It is also stated, "Hence, in all exact climatic studies, it is not only necessary to derive normals from a long period, say 35 years or more, but also to state the period taken, since a normal for the years 1800-1835 may very well differ from that for 1900-1935." Though not explicitly stated in the definition, it is implied that the normals are for a specific location.

After a study of the records, the period 1920-1951 was chosen as that which would give a normal most representative of the present rainfall regime. The definition of the word "normal" as used in this paper is, therefore, the mean monthly rainfall for a station at a fixed location for the 32-year period 1920-1951.

Description of the method--This paper is concerned with the problem of estimating normals for stations having records much shorter than 32 years. A hint as to a possible method was found in a paper by STIDD and LEOPOLD [1951], in which mean monthly rainfall values are correlated with annual averages. The following method was derived from this through discussion with Stidd and later with Glenn W. Brier, Chief of the Meteorological Statistics Section of the U. S. Weather Bureau.

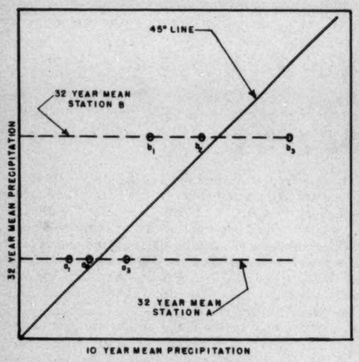

Fig. 1--Hypothetical variance of ten-year means

If the 30-year mean at a station were plotted against the means of the three ten-year periods making up the 30 years, it would be found that the ten-year means would be grouped about their mean, or, in other words, about the 45° line in Figure 1. This is illustrated by Station A. Because of correlation between stations, one would expect to find that if a certain ten-year period at Station A, say a-1, fell above the 45° line, this same ten-year period would fall above the 45° line for other stations in the area, such as b-1 at Station B. Furthermore, since one would expect that over a ten-year period the per cent of normal would be about the same at all stations, the station with the greatest 30-year mean rainfall would probably fall the farthest from the 45° line, as illustrated by Station B in Figure 1.

To test the hypothesis with some empirical data, the mean precipitation for the period 1920-1951 was plotted against the mean for each of the periods 1920-1931, 1932-1941, and 1942-1951 for each of 11 stations in the area of interest. Figure 2 shows that the theory fits well as all symbols representing a particular period fall on the same side of the 45° line and in most cases stations having the largest means show the greatest departures from the 45° line. A straight line drawn through the points representing a particular period, for example, the dashed line drawn through the X's in Figure 2, would come close to most of them. If the mean for a station for this period is known, a good estimate of its normal can be obtained from the dashed line.

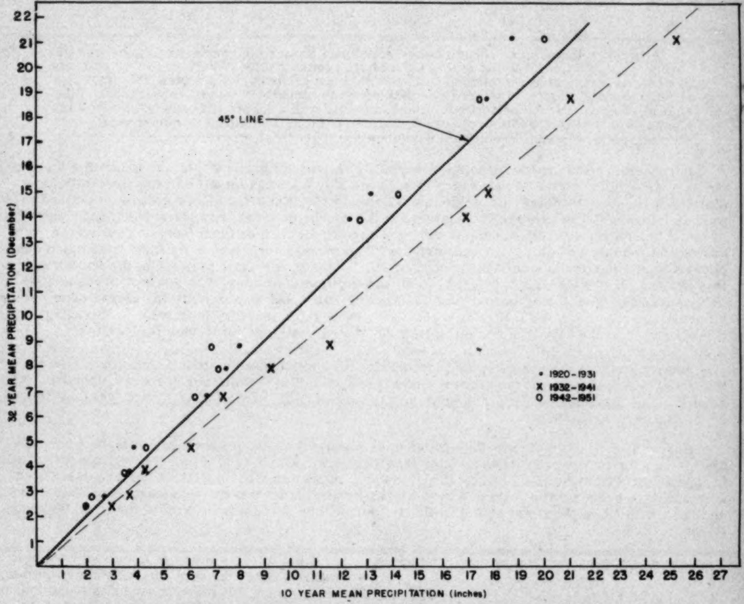

Fig. 2--Observed variance of ten-year means about the normal

Climatological Data normals--A more reliable estimate of the position of the straight line can be made by using more stations than above. As an alternative to computing normals for a large number of stations, it was decided to examine the normals published in Climatological Data to find if they are consistent with the definition of normal as given above.

To test this consistency a sample of stations in the area was selected and monthly rainfall values tabulated for the period 1920-1951. To determine the homogeneity of the rainfall record at each station the Double-Mass Curve Method described by KOHLER [1949] was used. Although somewhat subjective, the method is quite effective when used in conjunction with records of station location and movement. When the above analysis had been taken into account, the mean precipitation for the period was computed and compared with normals as obtained from Climatological Data. The results for the month of December are shown in Table 1. Due to the large differences, plus the knowledge that these normals are soon to be revised, it was decided that the normals as given in Climatological Data are not consistent with the definition of normal as used herein. The possibility of using these normals was, therefore, abandoned in favor of the actual mean precipitation for the defined period.

Table 1--Analysis for December based on Climatological Data

Station	Normal from Climatological Data a	32-year mean 1920-1951 b	Deviation a - b
	inch	inch	inch
Tatoosh	13.36	12.03	1.33
Rainier Longmire	13.09	14.41	-1.32
Quinault	20.66	21.23	-0.57
Olga	9.52	8.82	0.70
Olympia	9.21	8.50	0.71
Port Angeles	4.78	4.24	0.54
Tacoma	6.71	5.83	0.88

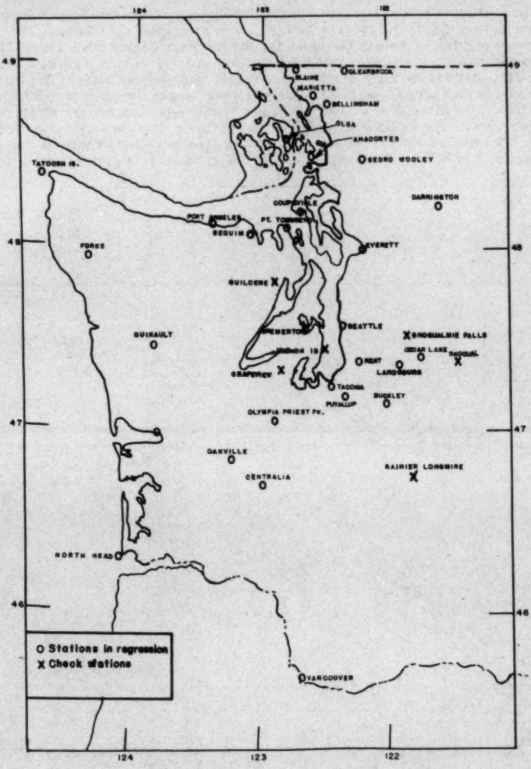
124
123
122
49
48
47
46
CLEARBROOK
BLAINE
MARIETTA
BELLINGHAM
OLGA
ANACORTES
SEDRO WOOLEY
TATOOSH IS.
DARRINGTON
COUPEVILLE
PORT ANGELES
PT. TOWNSEND
SEQUIM
FORKS
EVERETT
QUILCENE
SEATTLE
SNOQUALMIE FALLS
QUINAULT
BREMERTON
VASHON IS
CEDAR LAKE
SNOQUAL
KENT
LANDSBURG
GRAPEVIEW
TACOMA
PUYALLUP
BUCKLEY
OLYMPIA PRIEST PT.
OAKVILLE
CENTRALIA
RAINIER LONGMIRE
NORTH HEAD
VANCOUVER
O Stations in regression
X Check stations

Fig. 3--Location of stations in western Washington used to establish and check the regression lines

Application of the method to ten-year means--On reviewing the Climatological Data records, it was found that 46 of approximately 124 stations in operation in this area at the present time have a record of the required length for computation of these means. According to available station records, 30 of the 46 have been in the same location for the entire period, or have moved only a very short distance with no change in elevation. The locations of the 30 stations are shown in Figure 3. The only verification made of station location, because of time limitations, was a quick review of location records. A more thorough study would have included the previously mentioned double-mass curve analysis on each of the 30 station records to look for evidence of important station changes, comparing these with all possible sources of station location information, and making any indicated corrections. The assumption was made that such changes would balance out among the stations and, therefore, not affect the slope of the regression line to any great extent. The double-mass curves for a few stations used to establish the regression line have since been examined and all indicated corrections would have moved the stations data to or very near the regression line, which is strong support for the assumption.

Monthly precipitation totals, December through May, were tabulated from Climatological Data for the 32-year period (1920-1951) for each of the above mentioned 30 stations. The mean for this period was then computed as well as the mean for the ten-year period 1942-1951. The latter period of record was chosen because a majority of the stations seemed to have a record which included this interval. The stations having a shorter record will be discussed later. The ten-year mean for each station was then plotted against its 32-year mean and the method of least squares used to fit a straight line of the form, $Y = a + bx$. A sample scatter diagram for the month of December showing the regression line (solid line), is given in Figure 4. The correlation coefficient for this month is 0.98. The dashed lines on either side of the regression line represent one standard error, which for this month is 0.586. Since adjustment by the double-mass curve method would move the

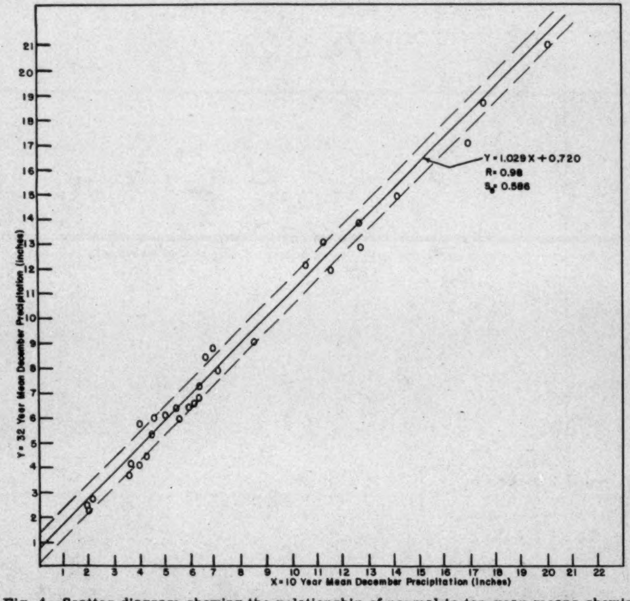

Fig. 4--Scatter diagram showing the relationship of normal to ten-year means showing fitted regression line (solid line) and one standard error of estimate (dashed lines) plotted points toward the regression line, this error in estimation would be reduced if all corrections were made. The correlation coefficient and standard error of estimate for each of the months computed to date, December through May, are given in Table 2.

Table 2--Correlation coefficient and standard error, December-May

Month	Coefficient of correlation	Standard error of estimate
December	0.993	0.586
January	0.991	0.586
February	0.990	0.476
March	0.995	0.316
April	0.994	0.209
May	0.982	0.258

Data from several stations with the required length of record, which had not been used in establishing the regression line because of doubtful records, have been adjusted by double-mass analysis. The normals have been computed and compared with the estimated values obtained by using the formula for the regression line. The results are shown in Table 3. The standard error of the 32-year mean is also included in Column d of Table 3. The error of the regression estimate, Column c, is very small relative to the standard error of the mean so makes very little contribution to the error.

Application to records of less than ten years--A number of stations in the project area have records less than ten years in length. To compute a mean based on this period of record, it is considered desirable to have exactly the same period of record used for all stations. For example, if a regression line is established using the five-year period 1942-1946 it could not be used to estimate the normal for a station having a record for the period 1943-1947. The correlation between years is very close to zero and, because of the large variability, a single value could greatly affect the mean of a small sample. Figure 5 shows the distribution of the five-year means about the normal. Except for one station which had to be eliminated because of missing data, the same stations are plotted here as were plotted on a similar graph for the ten-year means (Fig. 2).

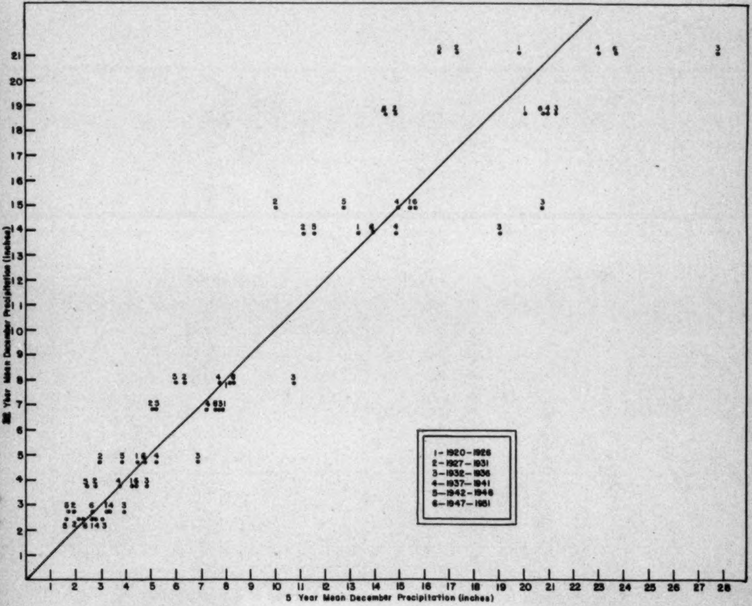

Fig. 5--Observed variance of five-year means about the normal

Table 3--Results after adjustment by double-mass analysis

Station	32-year mean December (1920-1951) a	Regression estimate b	Deviation (a - b) c	Standard error of 32-year mean d
	inch	inch	inch	inch
Grapeview	8.80	8.52	0.28	0.836
Quilcene	8.11	8.32	-0.21	0.817
Rainier Longmire	14.41	14.82	-0.41	1.191
Snoqualmie Falls	8.68	8.40	0.28	0.690
Snoqualmie Pass	18.18	17.96	0.22	1.720
Vashon Island	7.20	7.07	0.13	0.619

To establish five-year regression lines using all possible combinations of years would have been too great a task in the time available. As an alternative, stations within a radius of approximately 75 mi of the station in question were used. Their mean was computed using the exact years available at the station for which the normal was required, the points plotted, and the regression line drawn by inspection. This would appear to be a very rough approximation; but since the correlation is in most cases very near to unity, it is actually a very good approximation and the regression line is easily drawn.

Two additional regressions have since been computed for the month of December, one using a five-year mean (1947-1951) as the estimator and another using one year (1951) as the estimator. The scatter diagrams are shown in Figures 6 and 7. The solid lines are again the regression lines

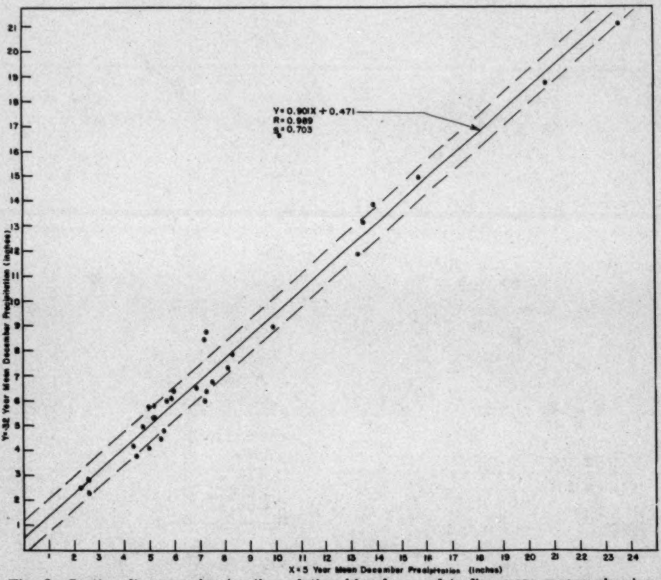

Fig. 6--Scatter diagram showing the relationship of normal to five-year means showing fitted regression line (solid line) and one standard error of estimate (dashed lines) and the dashed lines are one standard error above and below the regression lines. The correlation coefficient and standard error of estimate using the five-year mean as estimator are 0.989 and 0.703. The correlation coefficient and standard error of estimate using one year as the estimator are 0.947 and 1.227. As could be expected, there is an increase in the standard error of estimate with reduction in the length of record over which the mean is taken.

In Table 4 are tabulated the five- and one-year regression estimates along with their deviations from the computed normal for the stations used to check the ten-year regression. These estimates might be improved by selecting stations, with which to re-establish the regression line, from a smaller area surrounding the station to be estimated.

Table 4--Five- and one-year regression estimates

Station	32-year mean 1920-1951 a	Five-year estimate b	Deviation a - b	One-year estimate c	Deviation a - c
	inch	inch	inch	inch	inch
Grapeview[d]	8.80	. . .	. . .	7.41	0.39
Quilcene	8.11	8.04	0.07	10.56	-2.45
Rainier Longmire	14.41	12.83	1.58	14.06	0.35
Snoqualmie Falls	8.68	8.89	-0.21	11.03	-2.35
Snoqualmie Pass[d]	18.18	. . .	. . .	. . . .	. . .
Vashon Island	7.20	7.03	0.17	6.56	0.64

[d] Missing data.

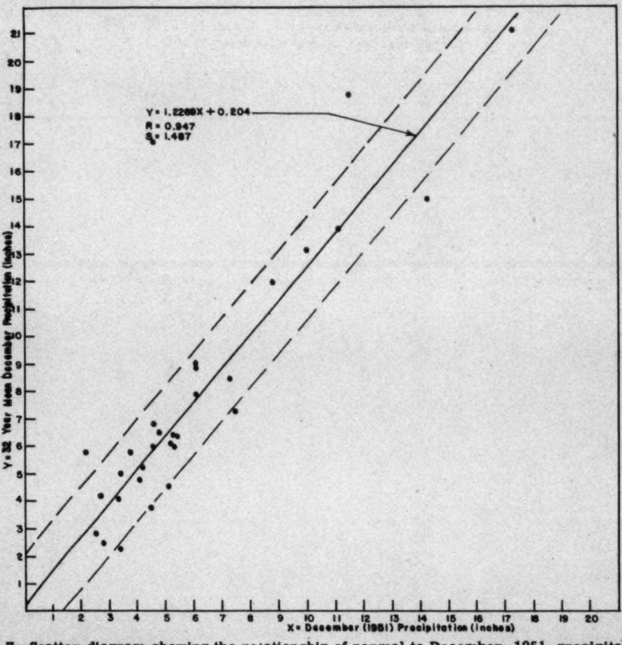

Fig. 7--Scatter diagram showing the relationship of normal to December, 1951, precipitation showing fitted regression line (solid line) and one standard error of estimate (dashed lines)

Summary--It is believed to have been shown here that normals can be estimated using this method for stations having as short a record as one year. The error decreases as the length of available record becomes longer, and this error can be estimated.

The method has been tested only for precipitation stations in western Washington for the months of December through May. It has yet to be tested for other meteorological parameters, areas, and months; but there is no obvious reason why it should not prove a good tool in all three cases.

An area in which the method might prove especially useful is Alaska, where only 35 of 130 stations have a record as long as 19 years and only 21 stations a record as long as 30 years. Here is an area in which the number of available normals could be more than doubled through the application of this method.

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STIDD, C. K., and LUNA B. LEOPOLD, The geographic distribution of average monthly rainfall, Hawaii, Meteorological Monographs, v. 1, no. 3, pp. 24-33, June, 1951.

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Washington 25, D. C.

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CHARACTERISTICS OF THUNDERSTORM MICROBAROGRAMS

Edward M. Brooks

Abstract--Each of 34 Friez microbarograph records of pressure variations associated with showers or thundershowers in the past five years near St. Louis has individuality, yet they indicate that there is an idealized thunderstorm microbarogram, which can be subdivided into five pressure stages. Each record exhibits at least one of the stages. Causes of the pressure changes are discussed.

Introduction--The 1948-1950 pressure traces used in this study were obtained with Friez microbarographs at the St. Louis Municipal Airport and at the author's home (four miles south of the Airport). The 1951-1953 barograms were obtained in a network of 11 stations (Table 1) with accelerated microbarographs in the St. Louis area. This network was established in 1951 to operate during the tornado season (Feb.-Aug.) each year in cooperation with the Tornado Project of the U. S. Weather Bureau, which organized a larger network in Kansas and Oklahoma in 1951. Both networks are operating again in 1954.

Table 1--Network of microbarograph stations, 1951-1954

No.	Station	Microbarograph	Speed of record
1	St. Albans Farms, St. Albans, Mo.	Friez microbarograph	1/2-day rotation, 1 in/hr
2	St. Stanislaus Seminary, Florissant, Mo.	Three Macelwane microbarographs	1.2 in/min
3	St. Louis Municipal Airport, U. S. Weather Bureau	Friez microbarograph	1/2-day rotation, 1 in/hr
4	St. Louis Municipal Airport, U. S. Navy Base	Friez microbarograph	1/2-day rotation, 1 in/hr
5	Author's home, Overland, Mo.	Friez microbarograph	1/2-day rotation, 1 in/hr
6	Home of J. Frohlichstein, cooperative observer, University City, Mo.	Friez microbarograph with Esterline-Angus recorder	0.8 in/hr
7	Institute of Technology, St. Louis University, St. Louis, Mo.	Friez microbarograph with Esterline-Angus recorder and Macelwane microbarograph	0.8 in/hr 1.2 in/min
8	Mallinckrodt Chemical Works, St. Louis, Mo.	Friez microbarograph loaned by Air Force Geophysical Research Directorate, Cambridge, Mass.	1/2-day rotation, 1 in/hr
9	St. Louis City Office, U. S. Weather Bureau	Friez microbarograpn	1/2-day rotation, 1 in/hr
10	Parks College of Aero. Tech., St. Louis University, E. St. Louis, Ill.	Friez microbarograph loaned by Air Force Geophysical Research Directorate, Cambridge, Mass.	1/2-day rotation, 1 in/hr
11	Scott Air Force Base, Belleville, Ill.	Friez microbarograph	1/2-day rotation, 1 in/hr

The purpose of the St. Louis network was to provide a close spacing of stations in order that the regional extent of thunderstorm pressure changes could be studied, whether or not tornadoes accompanied the thunderstorms. Except for St. Albans (30 miles west of St. Louis) and Scott Air Force Base (20 miles east of St. Louis), the stations were lined up roughly northwest to southeast from Florissant for a distance of 19 miles to East St. Louis across St. Louis (in order of number from 2 to 10 in Table 1). This gave a good cross-section because the line was nearly normal to the general southwest to northeast direction of motion of most thunderstorms.

Thirty-four Friez microbarograms from the author's records were selected for discussion. Some of these pressure traces along with one taken at the St. Louis Airport Office of the U. S. Weather Bureau are reproduced in Figures 1-5. The Macelwane microbarographs listed in Table 1 were used in a different phase of the project, concerned with pressure oscillations having periods less than one minute rather than several minutes.

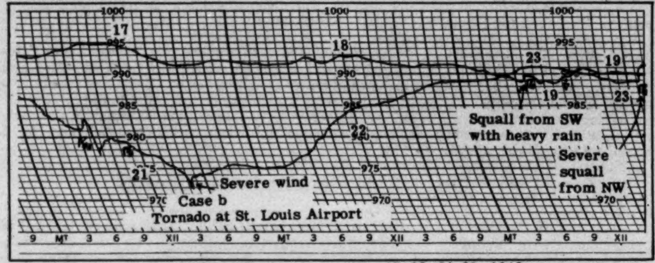


Fig. 1--Microbarogram for May 17-19, 21-23, 1949

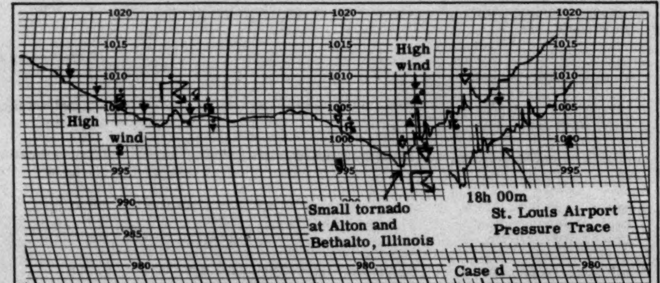


Fig. 2--Microbarogram for April 2-4, 1950

The records of thunderstorms, though having individuality, indicate that there is an idealized thunderstorm barogram which can be subdivided into five pressure stages. Each record exhibits at least one of these stages. They are arranged chronologically in Table 2 and Figure 6.

Stage A: Micro-low--Out of the 34 selected cases, only five exhibited Stage A, a sharply defined low barometer, usually lasting between ten minutes and a half hour when a thunderstorm is just beginning. Moving at an average speed of roughly 30 mi/hr, the low-pressure region causing this low barometer must average about ten miles wide (measured along its direction of motion).

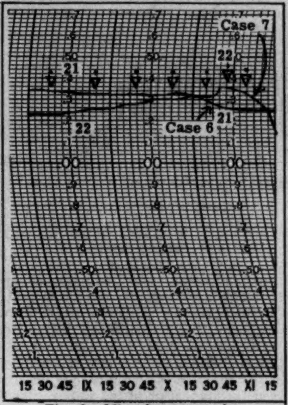
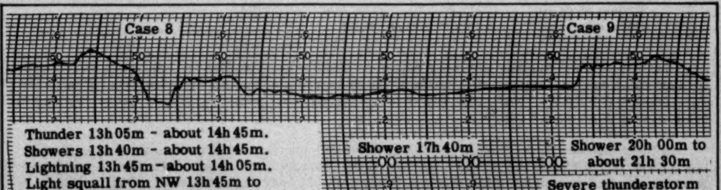


Fig. 3--Microbarogram for June 21-22, 1951

Two pressure distributions that might have caused the low barometer were considered: a sharp trough of low pressure about ten miles wide; or a roughly circular low, or micro-low, with a diameter of about ten miles. A trough would have given a low barometer at every station of the network in the St. Louis area. However, the microbarograph records showed that this never happened, but instead the low barometer occurred only locally at a few stations near each other. The evidence, therefore, indicates that Stage A was probably caused by a micro-low. Such micro-lows were found by WILLIAMS [1948] in a study of the March 19, 1948, data of the Cloud Physics Project of the U. S. Weather Bureau at Wilmington, Ohio.

A micro-low is important because it may be associated with tornadoes. Wind and pressure data at the time of the three tornadoes in St. Louis County, Missouri, on March 19, 1948, indicated to the author that these tornadoes were located inside a micro-low having a radius of about five miles [BROOKS, 1949]. (This was on the same day as Williams' micro-lows in Ohio.) This micro-low, intermediate in size between the size of the large occluding cyclone over northern Missouri and the size of the tornado funnels within it, was called a "tornado cyclone" by the author because the periphery of the micro-low seemed to be accompanied by an incomplete ring of strong cyclonically-curving winds, which was separated from the tornadoes by a zone of light winds. The tornado cyclone not only contains tornadoes within it, but it can contract to form an intense tornado. Such was the case with the tornado cyclone of March 19, 1948, which apparently contracted from its radius of about five miles to a radius of about a half mile by the time it crossed the Mississippi River into Illinois. By the principle of the conservation of angular momentum, the wind increased greatly, causing a severe tornado at Fosterburg and Bunker Hill.



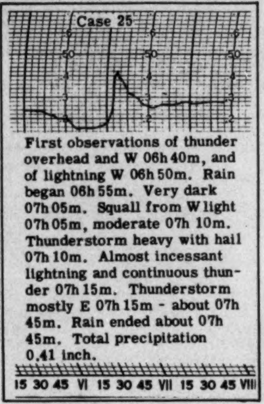
Thunder 13h 05m - about 14h 45m. Showers 13h 40m - about 14h 45m. Lightning 13h 45m - about 14h 05m. Light squall from NW 13h 45m to 14h 00m. Continuous thunder S 14h 00m. Moderate squall from E 14h 30m, and light squall from NW about 15h 00m converged to form low arched cloud from NW.

Shower 17h 40m

Shower 20h 00m to about 21h 30m

Severe thunderstorm N 20h 00m to 21h 00m starting with strong squall from NW

Fig. 4--Microbarogram for June 23, 1951



First observations of thunder overhead and W 06h 40m, and of lightning W 06h 50m. Rain began 06h 55m. Very dark 07h 05m. Squall from W light 07h 05m, moderate 07h 10m. Thunderstorm heavy with hail 07h 10m. Almost incessant lightning and continuous thunder 07h 15m. Thunderstorm mostly E 07h 15m - about 07h 45m. Rain ended about 07h 45m. Total precipitation 0.41 inch.

Fig. 5--Microbarogram for April 8, 1953

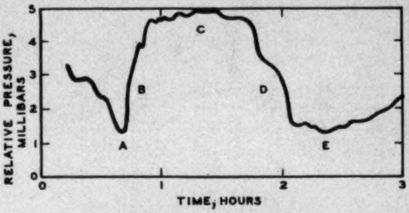


Fig. 6--Idealized thunderstorm microbarogram; letters refer to pressure stages

An example of a low barometer caused by a tornado cyclone is shown in Case b of Figure 1 at 16h 25m on May 21, 1949, when a tornado passed over the St. Louis Airport, four miles north of the barograph. The pressure fell two millibars from 16h 00m to 16h 25m, then suddenly rose 1.5 mb from 16h 25m to 16h 30m. During this time, a heavy thunderstorm was in progress behind (to the west of) the tornado. Precipitation had not started at the airport or at the author's house (location of the barograph).

Table 2--The five pressure stages of thunderstorm microbarograms

Stage	Name	Weather
A	Micro-low	Thunder audible in storm approaching from west, tornado possible.
B	Pressure rise	Squall wind and roll cloud from northwest, then heavy rain beginning.
C	Thunderstorm high	Middle of thunderstorm, hail possible.
D	Pressure drop	Rain ending, strong southeast wind.
E	Rear low	Thunderstorm ending.

Another tornado cyclone occurred between 10h 30m and 10h 45m on January 3, 1950, when a tornado aloft passed only one mile north of the barograph. The pressure dropped 1.5 mb, then rose one mb during the 15-minute period, when thunder was audible to the northwest without precipitation at the observing point.

In the remaining three cases, the micro-lows did not contain tornadoes when nearest the barograph, but in two of these cases tornadoes developed within these micro-lows a short time later before they reached the Mississippi River (May 9, 1949, and March 18, 1952).

Stage B: Pressure rise--Since nearly every thunderstorm is attended by a localized high-pressure area, it is preceded by a pressure rise. Some rise was found in all but one of the 34 selected barograms. As a general rule, the pressure rise is caused by the thunderstorm. The rate of rise is usually a fraction of a millibar per minute.

In some cases, the pressure rose very rapidly, the rate of rise equaling or exceeding one mb/min, and then remained high for an hour or even longer. TEPPER [1950] theorized that the pressure change in such a case was not caused by the thunderstorm, but that both the thunderstorm and the pressure rise were caused by a sudden increase in the height of an inversion aloft, in the manner of a hydraulic jump. He gave the sudden pressure rise the name of "pressure jump," whether or not a thunderstorm occurs with it. The theory is that when the pressure jump moves into a region where the atmosphere is potentially unstable, this instability may be realized, causing a line of thunderstorms to form. By tracing the progress of a pressure jump line, it should be possible to forecast where and when squall-line weather will develop. The Weather Bureau then equipped its first-order stations with gears for speeding up the rotation of the drums of the microbarographs so that a pressure jump with its sharp pressure rise could be distinguished from the ordinary pressure rise caused by a thunderstorm. The Weather Bureau defines a pressure jump as a rate of pressure rise exceeding 0.34 mb in two minutes, provided that (a) the amount of the rise is at least 0.68 mb, (b) the pressure remains at least 0.68 mb higher than the previous pressure for 20 minutes or more, and (c) the beginning of the pressure rise is not preceded by a pressure jump within the past 20 minutes; and, if the pressure was rising prior to the rise in question, the previous rate of rise was less than 0.34 mb in two minutes.

Out of the 34 cases, ten good examples of pressure jumps were found. In Case 9 in Figure 4, the pressure rose 2.7 mb from 19h 46m to 19h 48m (a rate of 1.35 mb/min) on June 23, 1951, attended by a strong squall from the northwest. A severe thunderstorm was centered nearby to the north from 20h to 21h. A pressure jump with a four-mb rise in ten minutes at 04h 00m on August 15, 1951, was accompanied by hurricane gusts from the northwest. The pressure remained four mb above the prevailing pressure for five hours (until 09h 00m). The pressure jump with the largest rise was that of April 8, 1953, when there was a remarkable rise of 8.5 mb in only eight minutes (07h 00m to 07h 08m), followed by a fall of 5.5 mb by 07h 30m (Fig. 5). It was very dark with a squall from the west at 07h 05m. Hail occurred during a heavy thunderstorm at 07h 10m. There was almost incessant lightning and continuous thunder at 07h 15m.

A pressure jump line may be attended by tornadoes. The tornadoes do not have to occur before the pressure jump, but may follow within five minutes after the pressure jump. During these five minutes, cool outflow air from the thunderstorm is present at low levels, having arrived with the roll cloud, while the warm air at the surface is not yet displaced by the cool outflow air. This happened in two instances: at 23h 30m on May 1, 1948, in southern St. Louis, and at the author's house on March 31, 1952. In the latter case, the tornado was fortunately very minor. The wind came with a growing roar, then faded away within a minute (20h 39m to 20h 40m). At the same time the pressure fell and rose a half mb, immediately following a pressure jump with a two-mb pressure rise from 20h 37m to 20h 39m.

On the other hand, at least two pressure jumps occurred with no weather disturbance at all, such as the case of August 25, 1950, when the pressure rose 1.3 mb at 19h 00m. Prior to this time, thunderstorms were occurring in Missouri to the west. When there was little or no precipitation with a pressure jump, it was found to be in the dying stages. The author has not found any case of a fair-weather pressure jump in the St. Louis area which later developed squall-line weather.

Stage C: Thunderstorm high--It may be hypothesized that the localized high pressure which accompanies a thunderstorm is primarily hydrostatic, but that it may be augmented dynamically. The hydrostatic effect of the relatively cool air in the lower portion of a mature thunderstorm is to give high pressure under it. However, cooling alone cannot account for high pressure unless an additional mass of air is added to the air column by horizontal convergence. Such convergence has been found to occur above about 5000 ft from data gathered in the joint Thunderstorm Project [BYERS and BRAHAM, 1949]. The amount of convergence is much greater than the frictional convergence of air into the general trough of low pressure in which the thunderstorm is generally located. A local cause for the convergence into a thunderstorm is perhaps the low pressure located within the region of strong vertical currents aloft. The entrainment of air into the vertical currents is aided by the internal friction between these currents and their environment. A partial filling of the low aloft results in a surface high-pressure area. Another factor contributing hydrostatically to the high surface pressure is the weight of the large amounts of liquid water and ice in the air column.

The dynamic effect of vertical motion on surface pressure depends on the causes of the acceleration and retardation of the vertical currents. If the vertical acceleration is entirely due to a lack of balance between the vertical component of the pressure gradient and gravity, then the dynamic effect is merely the Bernoulli pressure drop, proportional to the square of the vertical speed, and the effect is not present at the surface, where the vertical speed is zero. On the other hand, if the downdraft is caused by the frictional drag of falling precipitation, the downdraft is not attended by the Bernoulli pressure drop [BROOKS, 1951]. Instead, as the downdraft approaches the surface, it creates a compressive pressure rise of the same magnitude. The resulting vertical pressure gradient exceeds gravity by the amount required to explain the retardation of the descending air. A microbarograph record made under a strong downdraft shows the dynamic pressure rise as a "pressure nose" superimposed on the thunderstorm high [BYERS and BRAHAM, 1949].

The thunderstorm high endures after the thunderstorm and even after the shower have dissipated. Case 8 in Figure 4 illustrates such a high. The first high occurred with a mature thunderstorm at 14h 00m on June 23, 1951, whereas the second high between 15h 00m and 16h 00m represented the remnants of a thunderstorm, no longer active, from which no rain fell. Case 7 of June 22, 1951 (Fig. 4), shows a less pronounced high associated with a shower, which probably was a thundershower before reaching St. Louis.

It is not uncommon for a thunderstorm high to last at an observing point for half an hour, an hour, or even longer in some cases, such as in Case 9 (Fig. 4) from before 20h 00m to after 21h 00m on June 23, 1951, or in the case of August 15, 1951, from 04h 00m to 09h 00m. (Both of these cases are discussed in connection with pressure jumps under Stage B above.) On the other hand, many highs last only a matter of minutes or less. A succession of these highs with small amplitudes, occurring under conditions which do not produce thunderstorms, may be due to minor oscillations in the height of an inversion. However, with thunderstorms, there are some short-period highs that have large amplitudes and appear on the barograms as sharp peaks of high pressure rather than smooth sinusoidal waves. These sharply-defined highs are attended by strong downdrafts and relatively cool air columns. Case d in Figure 2 illustrates a series of these small highs, two of which were associated with hail storms on April 3, 1950. In the first storm at 19h 50m, hail a half inch in diameter with some one-inch stones covered the ground, and the pressure rose and fell suddenly two mb. In the second storm at 20h 35m, there were only a few hailstones, but the pressure change had a greater amplitude of five mb. The pressure rose so suddenly that it could be felt in one's ears, as if one were descending in an elevator or airplane. These micro-highs, unlike the micro-lows (described under Stage A above), were not circular in shape, but were long narrow wedges with a north-south orientation. This is shown by the nearly identical pressure trace recorded at the St. Louis Airport four miles to the north (Fig. 2). These highs, lasting less than five minutes, were less than four miles wide, measured west to east, the direction of their motion.

Stage D: Pressure drop--The pressure drop on the rear side of a thunderstorm high has not received as much attention from meteorologists as the pressure rise in front of the high, perhaps because the drop is usually more gradual than the rise. The pressure drop achieves importance in many cases where it is sudden and large, bringing the pressure to a lower level than existed prior to the storm (see Stage E below). Such a pressure drop is accompanied by moderate or strong east or south-east winds blowing out of the thunderstorm high to the east. This surface air flow out of the rear side of the thunderstorm is subjected to this east-west pressure gradient for an even shorter time than the gradient exists at a fixed observation point, whereas, on the front side of the thunderstorm high, the air moving in the same direction as the thunderstorm is subjected to the west-east pressure gradient for a longer time than the gradient exists at a fixed point. The rear outflow is not as strong as the front outflow, and the rear outflow blows at a larger angle across the isobars than the front outflow because of the shorter time that the pressure gradient force and the Coriolis force act, respectively, at the rear.

A remarkable case of a line of large pressure drops accompanying strong winds on April 11, 1944, was traced across the middle part of the United States by BRUNK [1949]. A more recent case occurred in St. Louis at 05h 00m on September 17, 1952, when the pressure dropped 2.5 mb in four minutes, and there was a severe wind from the southeast, at the end of a thunderstorm high lasting 4.5 hours (beginning at 00h 30m). Examples of pressure drops on the rear side of showers are shown in Cases 6 and 7 (Fig. 3) for June 21 and 22, 1951.

The pressure drop on the rear side of a squall-line thunderstorm has been responsible for errors in map analysis. When the map analyst sees a report of rapidly falling pressure, strong southeast wind, and high dew point, he is inclined to think that the squall line has not yet arrived at that station because he may not be aware of the clearing trend of the weather normally occurring at this stage. This error in interpretation can be avoided if the analyst notes that a measurable amount of precipitation has just occurred and that the past weather is reported as a thunderstorm. The report also shows relatively low temperature, characteristic of thunderstorm outflows, unlike the high temperature of the warm sector. These are clues to the arrival and passage of the squall line prior to observation time.

Stage E: Rear low--In six of the 34 selected cases, a clearly defined low pressure followed the shower or thundershower. This rear low differs greatly from the micro-low ahead of the thunderstorm in that the surface air in the rear low consists of the relatively cool outflow air of the receding storm, whereas the micro-low has warm surface air which has not yet been affected by the approaching storm. The cool outflow air underlying the prevailing warm air mass makes the thermal stability of the rear low much greater than that of the micro-low ahead of the storm.

Case 8 in Figure 4 shows a pronounced low between two thunderstorm highs on June 23, 1951. Even though such a low may precede one or more highs, it must always be classified as a rear low because of the cool surface air in it resulting from the first storm. In Case 8, the thunderstorm highs were so close together that their two outflows converged to form a low arched cloud moving from the northwest with the rear low. If it were not for the thermal stability at the inversion between the cool and warm air, the converging and rising air would not have stopped, but would have developed into a rapidly growing cumulus cloud and a cumulonimbus cloud, and might have even formed a tornado. The thermal stability thus prevents tornadoes from developing behind a thunderstorm or between two closely spaced storms, even though the horizontal convergence at the surface may be very great.

An inspection of barograms reveals that the depression of a rear low or a micro-low ahead of a thunderstorm is about the same as the excess of pressure in the thunderstorm high (see the pressure trace for the morning of May 21, 1949, Fig. 2). This suggests that during the formation of the thunderstorm the convergence of air into the air column of strong vertical currents not only accounts for the generation of the thunderstorm high, but also the nearby low. Whether the low forms ahead of or behind the high seems to depend on the source of the thunderstorm convergence. If the air is drawn largely from the front of the storm, a micro-low develops, and if the inflow becomes strong enough, a tornado may form. On the other hand, if the inflow is mainly from the rear, a rear low develops. No cases were found where both a front micro-low and a rear low were present in connection with the same thunderstorm high. There were many cases where no low appeared on the microbarogram next to the thunderstorm high, because either the low was on a flank rather than in front of or behind the high, or the convergence was so symmetrical that a small undetectable pressure fall occurred in a large area surrounding the high.

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SOME RESULTS OF A TANKER SURVEY OF THE GULF STREAM

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Abstract--An analysis is made of oceanographic observations taken aboard tankers over a period of one year between Key West and Cape Hatteras. The Gulf Stream is shown to have seasonal and tidal fluctuations in speed and position. Meanders, known to exist to the north, are shown to exist as far south as the Straits of Florida.

Introduction--Although for many years an object of intense curiosity, the Gulf Stream system has remained a vague and deceptive phenomenon. A multiple-ship survey was carried out during the month of June, 1950, by vessels of the Woods Hole Oceanographic Institution, U. S. Navy Hydrographic Office, U. S. Fish and Wildlife Service, and the Canadian Navy. This expedition

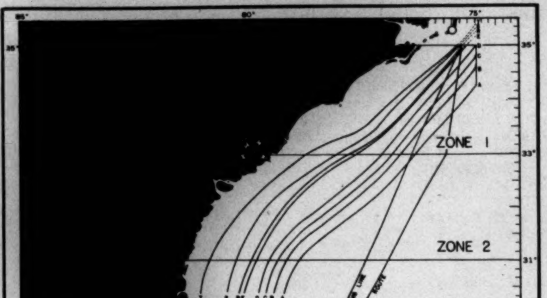


Fig. 1--Tracks employed in the Gulf Stream Tanker Survey; tracks A to E are for northbound trips; R, S, T, and the Outside Route for southbound courses; the rhumb line was not actually followed by the tankers but is shown for comparison; the area studied is divided into six zones for convenience of computation brought into focus for the first time a quasi-synoptic picture of the Gulf Stream front between Cape Hatteras and 50° W. Simultaneously, and for a year thereafter, the Hydrographic Office collected hourly reports from oil tankers traveling between Cape Hatteras and the vicinity of Key West. This paper presents some of the results obtained in the latter survey.

The techniques employed in the two investigations differed considerably. In the multiple-ship survey, six ships were spaced at roughly equal intervals along the Gulf Stream and zigzagged along the current path while recording the pertinent data. In the Gulf Stream Tanker Survey, the Hydrographic Office was dependent upon Loran-equipped commercial vessels for information. Only such observations as could be made without disturbing the normal courses of the tankers were available. Fortunately, however, tankers generally prefer a course as close as possible to the axis of the Gulf Stream on their northbound passages (Fig. 1).

A group of tankers was persuaded to vary courses from one passage to another so as to provide data over the sequence of recommended tracks. Track C represents the course which was normally followed by most of the tankers. So greatly was track C favored that three times as many reports were received for this track as for the others. For southbound tankers, the most preferred route was the Outside Route.

The tankers recorded hourly Loran fixes, dead-reckoning courses and speeds, sea surface temperatures, sea state, and meteorological observations. The differences between the Loran fixes and dead-reckoning positions are assumed to represent the current set and drift, for, although the wind also must have a slight effect, it is believed that oil tankers, particularly when loaded, must be influenced predominantly by surface current.

Observations made during the period May 1, 1950, to May 1, 1951, representing a total of 94 northbound and 62 southbound passages, were recorded. The average time required for a passage from 27° to 35° N lat was about 35 hours. There were available, therefore, over 5000 hourly observations. It is believed that such statistical results as have been obtained may be regarded as valid.

Temperature--Among the types of data obtained from the tankers were sea-water injection temperatures (taken at a depth of 15 to 30 ft) read at hourly intervals. The manner in which the tankers followed specified tracks provided an interesting opportunity to study the fluctuations of sea temperature from point to point along track C and from month to month throughout the year. Figure 2 shows the mean temperatures along track C by seasons. Although the temperatures drop

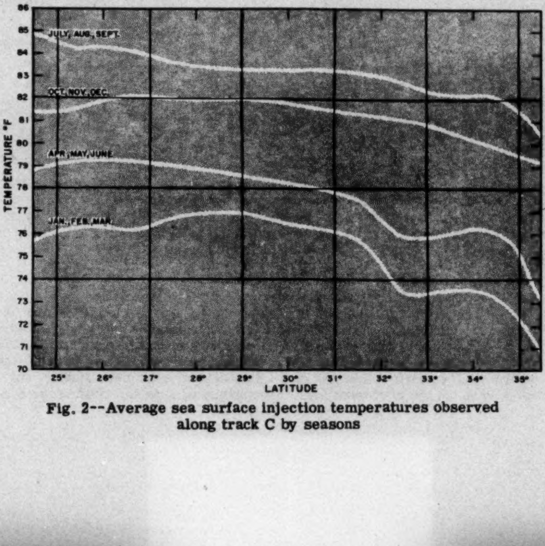


Fig. 2--Average sea surface injection temperatures observed along track C by seasons as might be expected from the Straits of Florida toward Cape Hatteras, there are some departures from this rule. For example, the highest temperatures along track C during the winter months (January, February, March) appear at 29° N. Also, during the winter and spring months there is a curious minimum at 32° to 33° N. The apparent loss of temperature of the Gulf Stream water is as much as 6°F in the winter and spring months between the Straits of Florida and the latitude of Cape Hatteras. In the autumn (October, November, December) this loss has diminished to less than 3°F.

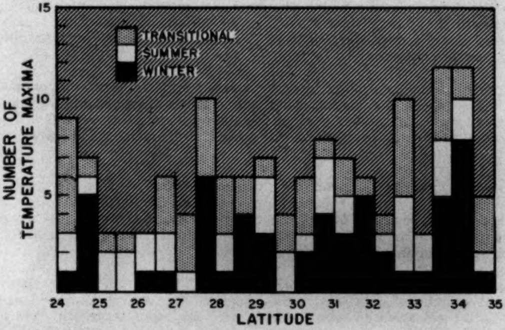


Fig. 3--Relative frequency of occurrence of sea surface (injection) temperature maxima for individual passages at the indicated latitudes

Figure 3 illustrates the distribution of temperature maxima along track C. For each successive passage, the hours for which the sea temperature reached a value higher than that for the preceding and following hourly observations were recorded. These maxima were totaled for each one-half degree interval of latitude, and illustrated graphically by seasons as shown. The objective here is to demonstrate, if possible, the points at which the warm temperature core of the Gulf Stream crosses track C. Figure 3 appears to indicate that there are certain latitudes at which such crossings occur with a greater than random frequency.

Injection temperatures are known to be subject to errors inherent in the recording devices and arising from the lack of uniformity in level of intake of the sea water. One ship passing through a particular area may record the temperature as slightly different from the reading observed by another ship in the same area. Injection temperatures, as treated in this discussion, are considered as relative to other readings by the same ship. Temporal and areal comparisons of the data from a number of ships are made in such a manner as to cancel out most of the error associated with injection temperatures.

Current rips--Tankers were asked to note the occurrence of current rips in their reports. The physical meaning of current rips in the open ocean has never been clear. When observed in the vicinity of the Gulf Stream, their occurrence seems to be related in some way to the dynamics of that giant current. Most current-rip reports from the tankers were obtained during the summer months. This may be in part the result of the relative calm which characterizes the sea during that portion of the year, rendering the current rips visible.

Current rips were studied in relation to latitude. Figure 4 shows the frequency of the reports by one-half degree intervals of latitude. There is a marked occurrence of rips at 31.5°N with lesser groupings at other latitudes. The latitude 31.5°N is approximately the latitude at which the Gulf Stream goes into a sharp bend. To further check this phenomenon, the authors analyzed current-rip reports from the vicinity of the Gulf Stream which had been submitted to the Hydrographic Office over a period of 20 years by other vessels. This second and independent group of data shows the same pattern in which the rips were most often observed near the bend in the Stream.

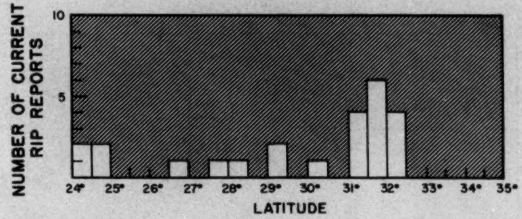


Fig. 4--Relative frequency of current-rip reports along track C with latitude

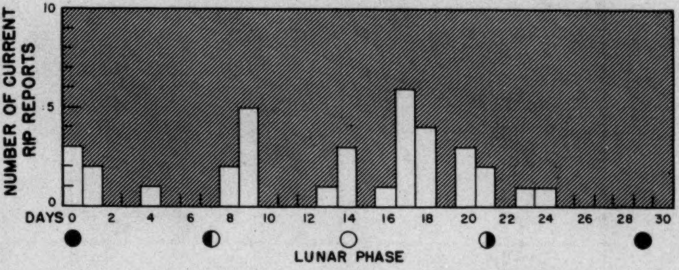


Fig. 5--Frequency of current rips in relationship to lunar phase

Finally, the current-rip data were screened in accordance with their occurrence relative to lunar phase (synodic month). The result of this is shown in Figure 5. The distribution does not appear to be random. The largest grouping of data occurred on the 17th day of the synodic month. An interpretation of this fact must await better knowledge of the Gulf Stream. This phenomenon does, however, suggest an oscillation of the current axis in phase with the synodic cycle.

Steering anomalies--In addition to the more obvious oceanographic parameters, the authors undertook a study of "steering anomalies." A steering anomaly consists of the number of degrees by which, in a given instance, a tanker departs from her desired course in order to compensate for the lateral drift caused by cross current. The steering anomalies for the winter and summer seasons are shown in Figure 6. Because of the relative abundance and simplicity of this type of data, they were thought to be promising as a means for analyzing the flow pattern.

To visualize the meaning of the above data more easily, Figure 7 has been devised. The percentage of hourly reports for which a component of the cross current set normal to one side or the other of track C is shown for the period of a year. The directions of the cross currents are not evenly divided as setting toward one side of the track or the other, but rather show a high frequency of flow from a particular side at certain latitudes.

Seasonal variation of currents--As a convenience in computing the currents, the area to be studied was divided into the zones shown in Figure 1. In Figure 8, mean effective currents along each track and within each zone are shown for each tanker passage. Although there is a considerable variation from one passage to another, there is a detectable seasonal variation in current speed. There are two seasonal maxima in zone 1, while there are apparently four such maxima in zone 4.

The seasonal variation of current speed in zone 4 has been studied as shown in Figure 9. Zone 4, which is just to the north of the Straits of Florida, was chosen to illustrate the seasonal effect

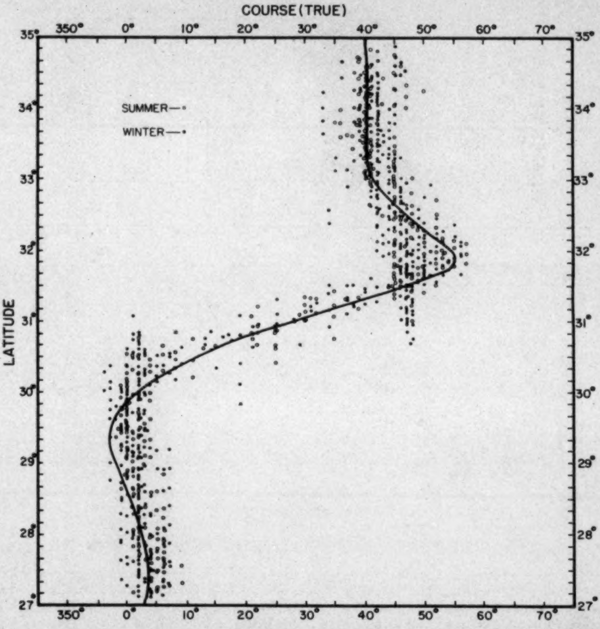


Fig. 6--Steering anomalies for the winter and summer seasons; the solid line represents the courses steered by a hypothetical tanker passing along track C which experienced no cross-course drift; the circles and dots represent the actual courses steered by tankers at a particular latitude; the departure of the actual courses from the hypothetical is believed to indicate the points at which there have been cross currents along track C and provides an indication as to the location of the Gulf Stream axis

further, as it was believed that here the lateral fluctuation of the current axis is minimized. The maximum speed in July is in agreement with the findings of other investigators of the seasonal fluctuation in this area [FUGLISTER, 1951; ISELIN, 1940]. The fact that the tanker-observed variations in speed roughly fit the sea level curve indicates that the tanker data are probably representative of the total cross-sectional flow of the Stream.

Variation of currents by tracks--The mean effective current speeds have been combined by tracks and by zones into mean annual curves as shown in Figure 10. Below 27°N lat, where tanker data were sparse, the results of PILLSBURY's [1890] observations were employed to complete the picture. It should be recognized that the speeds indicated are less than the actual speeds which may occur in reality (up to five knots), having been reduced by the averaging process together with the fact that the current component normal to the tanker track is neglected. Of special interest here are the double maxima which appear in certain of the zones. These suggest either a split current axis or two often-frequented positions of a single current axis.

Tidal fluctuations in the current--The analysis has shown an apparent tidal periodicity in the Gulf Stream flow. Tidal periodicities were first discussed by PILLSBURY [1890]. It was his

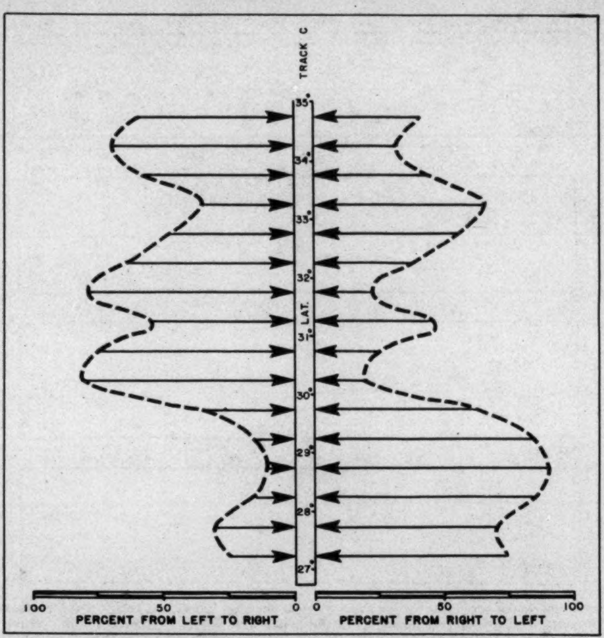


Fig. 7--Percentage frequency of cross currents normal to track C in the sense indicated as determined from an analysis of steering anomalies

suggestion that the current speed and position of the axis are influenced by lunar declination. He found that in the Straits of Florida the stream broadens and slows down at maximum declination while at zero declination it narrows and speeds up.

The tanker speeds in zones 1 to 4 (Fig. 11) show a marked fluctuation when considered in relation to declination, but the relationship seems to be the inverse of that found by Pillsbury. More study will be necessary to understand the reasons for this conflict. Although Pillsbury did not indicate a current fluctuation as related to lunar phase in this region, such a fluctuation was found to exist in zones 1 to 4 of the tanker survey. The curve has a different shape in zone 4 (off Florida) than it has in the three more northern zones.

Pillsbury found that maximum current speed followed lunar transit over the local meridian in the Straits of Florida by 3 hr 40 min. PARR [1937] has noted "extrusions" along the stream of apparently lunar periodicity. MURRAY [1952] has reported that there are counter-currents of lunar periodicity along the shoreward edge of the Gulf Stream. An attempt was made to screen the tanker survey data for a semidiurnal tidal periodicity but the results obtained thus far have been inconclusive.

Meanders along the Gulf Stream--A number of analyses of the observations of individual tanker passages was made. A typical analysis is shown in Figure 12 for a passage which occurred during June, 1950. The shaded band represents the authors' interpretation of a meander along the stream.

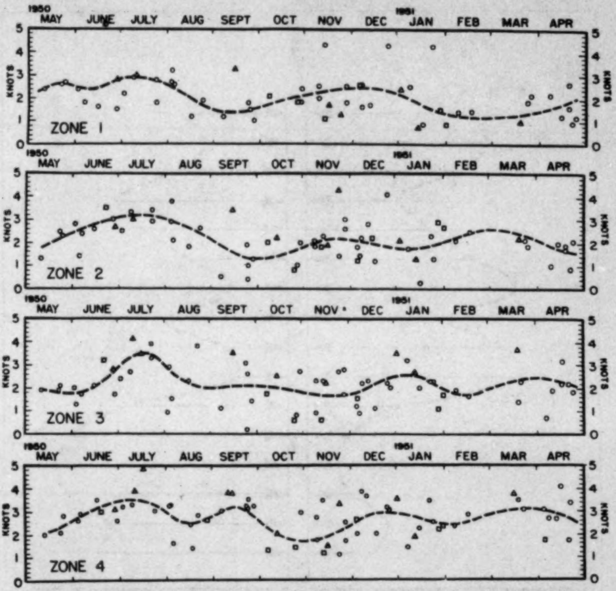


Fig. 8--Mean effective currents as experienced by individual tankers in relation to the time of year; the locations of the zones are shown in Figure 1; the circles represent currents on track C, the triangles track D, and the squares track B

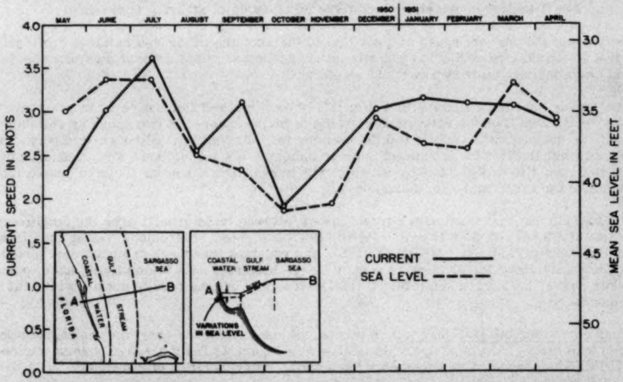
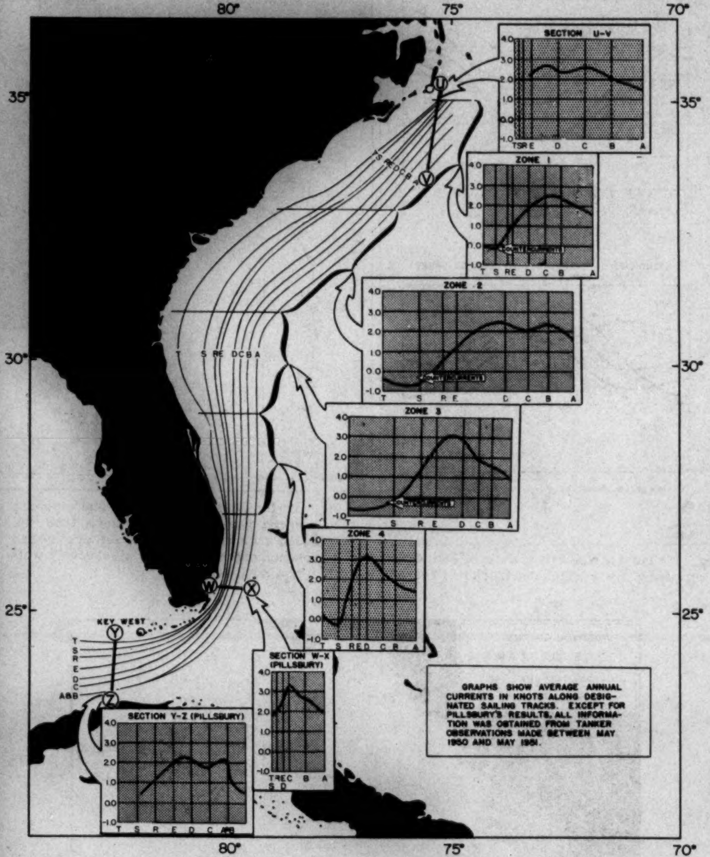


Fig. 9--Seasonal fluctuation of current speed in zone 4 (off Florida) in comparison with sea level fluctuations at Miami; the sea level data were supplied through the courtesy of the Tides and Current Division, U. S. Coast and Geodetic Survey


80°
75°
70°
35°
30°
25°
SECTION U-V
ZONE 1
ZONE 2
ZONE 3
ZONE 4
SECTION W-X (PILLSBURY)
SECTION Y-Z (PILLSBURY)
KEY WEST
U
V
W
X
Y
Z
T S RE D C B A
4.0
3.0
2.0
1.0
0.0
-1.0

GRAPHS SHOW AVERAGE ANNUAL CURRENTS IN KNOTS ALONG DESIGNATED SAILING TRACKS. EXCEPT FOR PILLSBURY'S RESULTS, ALL INFORMATION WAS OBTAINED FROM TANKER OBSERVATIONS MADE BETWEEN MAY 1950 AND MAY 1951.

Fig. 10--Schematic representation of the mean effective current speed along the Gulf Stream

Similar meanders were observed during the passages at various times of the year. In none of the passages studied did the Gulf Stream appear to be free of the phenomenon of meandering.

The wavelength of the meanders observed during the tanker survey, as nearly as they could be measured, was about 120 mi. Although tanker passages occurred as frequently as one day apart, it was not possible to identify with certainty a particular meander from one passage to another. For this reason no reliable estimate of the rate of migration can be made.

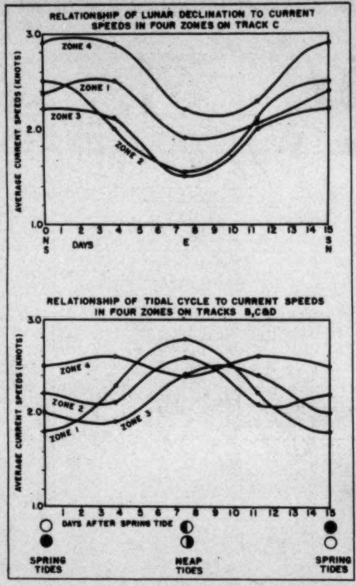


Fig. 11--Tidal periodicity of mean effective current speed along designated tracks, by zones

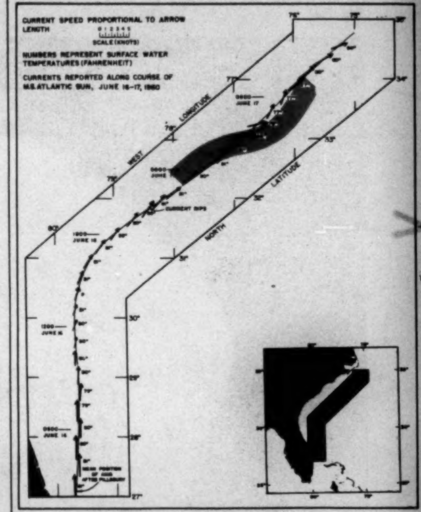

CURRENT SPEED PROPORTIONAL TO ARROW LENGTH
0 1 2 3 4 5
SCALE (KNOTS)
NUMBERS REPRESENT SURFACE WATER TEMPERATURES (FAHRENHEIT)
CURRENTS REPORTED ALONG COURSE OF M.S. ATLANTIC SUN, JUNE 16-17, 1950
WEST LONGITUDE
NORTH LATITUDE
76°
75°
77°
78°
79°
80°
35°
34°
33°
32°
31°
30°
29°
28°
27°
0600 JUNE 17
0600 JUNE
CURRENT DIPS
1800 JUNE 16
1200 JUNE 16
0600 JUNE 16
MEAN POSITION OF AXIS AFTER PILLSBURY

Fig. 12--Injection temperatures and currents observed by a tanker during June, 1950; the shaded area represents the authors' interpretation of the position of a relatively well defined meander

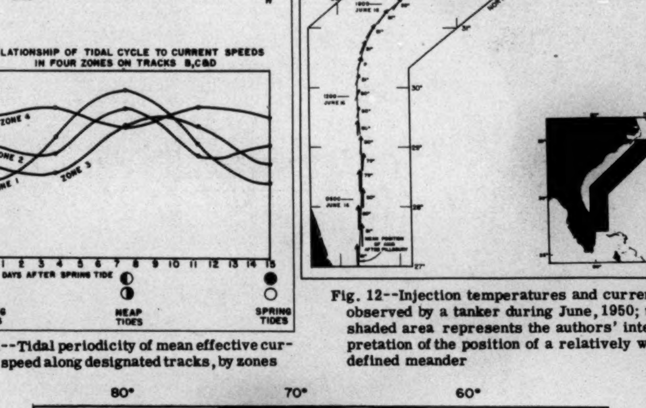

80°
70°
60°
40°
30°
POSITION OF THE GULF STREAM
7-12 JUNE 1950
19-24 JUNE 1950
19-24 JUNE
7-12 JUNE
POSITION OF GULF STREAM AXIS AS DETERMINED BY "OPERATION CABOT"
POSITION OF GULF STREAM AXIS AS DETERMINED BY TANKER SURVEY

Fig. 13--The Gulf Stream front during June, 1950; Operation Cabot was the code name assigned to the multiple-ship survey

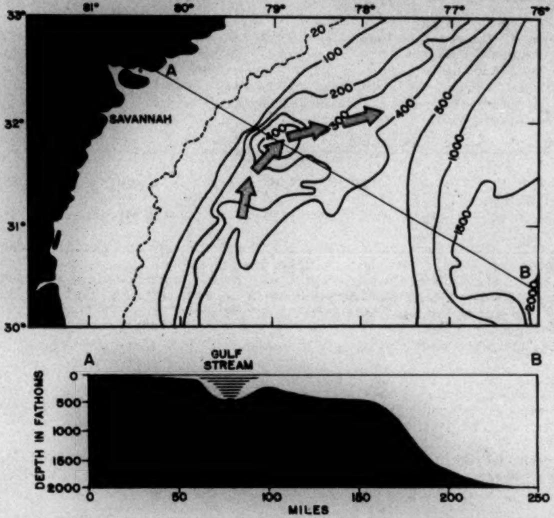

33°
81°
80°
79°
78°
77°
76°
32°
31°
30°
SAVANNAH
A
B
20
100
200
300
400
500
1000
1500
2000
GULF STREAM
DEPTH IN FATHOMS
0
500
1000
1500
2000
0
50
100
150
200
250
MILES

Fig. 14--Relationship of the Gulf Stream path to bottom topography

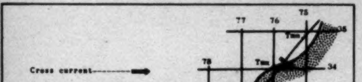

Cross current
Temperature maximum--Tmx
Temperature minimum--Tmn
Current rip--R
75
76
77
78
79
80
81
82
83
35
34
33
32
31
30
29
28
27
26
25
24
23
Tmx
Tmn
R
Track "C"

Fig. 15--Mean annual path of the Gulf Stream as derived from a study of steering anomalies, temperature maxima, and current rips

The meanders observed by the multiple-ship survey in June, 1950 [FUGLISTER and WORTHINGTON, 1951], had wavelengths in excess of 200 mi. The relationship between the meandering of the Gulf Stream as observed by the multiple-ship survey and the meandering as observed by the tanker survey during the same period is shown in Figure 13.

Bottom topography--The Gulf Stream follows a path from Key West to Cape Hatteras which closely parallels the inner continental slope (100-fm line). To the east of the Bahamas there extends a deeper and more marked continental slope. The relationship of the path of the Gulf Stream to the submarine topography is brought out in Figure 14. A curious feature of this relationship is the depression beneath the path of the stream near 32°N. This depression and the double-platformed shelf in this area are suggestive of submarine fluid erosion. The question is raised for the submarine geologist as to whether the Gulf Stream is guided in its path by the topography of the shelf or whether the shelf has been modified by erosion so as to allow the Gulf Stream to follow a path dictated by the dynamics of the current.

Summary--While much descriptive information about the Gulf Stream system has evolved from the tanker survey, it has not answered questions concerning the origin and rate of migration of the meanders. The observed fluctuations in current speed suggest that tidal forces may play a role in the origin and maintenance of the meander. The evidence of the multiple ship survey of June, 1950, would indicate that the rate of migration is about 11 mi per day. A comparison of one tanker passage with another indicates that meanders are not always in the same position. On the other hand, a statistical summation of many passages indicates that meanders may be fixed in certain localities (Fig. 15).

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A CONTRIBUTION TO THE THEORY OF UPWELLING AND COASTAL CURRENTS

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(Contribution from the Department of Oceanography of the Agricultural and Mechanical College of Texas, Oceanographic Series, No. 31)

Abstract--A theory of upwelling and coastal currents induced by longshore and offshore winds is derived, taking the effects of Coriolis forces and horizontal and vertical mixing into account. In the first place, it is shown that an upwelling circulation can be caused in the vertical plane perpendicular to the coast by a wind blowing parallel to the coast in such a manner that, in the northern (southern) hemisphere, the coast is on the left-hand (right-hand) side of an observer with his back to the wind. The result agrees with the facts observed in the regions off the Southern Californian and Peruvian coasts very satisfactorily. The velocity of upwelling is computed at about 80 m/month, a value consistent with that estimated from observed hydrographic data. Next, it is shown that an offshore wind blowing perpendicular to the coast can also give rise to a similar circulation in the same vertical plane, but in this case with much weaker intensity. From these results it can be concluded that the most intense upwelling will occur when the wind makes an angle of 21°.5 with coast line in an offshore direction. In addition to these circulations in the vertical plane, there exist horizontal currents parallel to the coast. These will contribute to the formation of the coastal or longshore currents much debated recently. The horizontal components of the motion under consideration show a vertical variation very similar to the Ekman spiral at some distance from the coast.

Introduction--There have been several descriptions of upwelling observed off Californian, Peruvian, West African, and other coasts by THORADE [1909], McEWEN [1912, 1929], GUNTHER [1936], DEFANT [1936, 1952], SVERDRUP [1931, 1938], and SVERDRUP and FLEMING [1941]. The explanation of this process given by SVERDRUP [1938] is worth attention. According to SVERDRUP and Others [1942], it is known from analysis of the water masses that the water taking part in the process of upwelling off the coast of Southern California originates primarily in the layers from 200 to 300 m below the surface. These are, however, all qualitative discussions and it has not yet been possible to explain this phenomenon theoretically and predict the velocity and width of coastal currents produced by the prevailing winds. Recently DEFANT [1952] made a theoretical explanation assuming a sea consisting of two layers of water with different densities. The present research is an attempt to solve this problem mathematically and to draw some quantitative conclusions concerning this process which is very important in all fields of oceanography.

The only satisfactory explanation of upwelling seems to come from treating the problem thermodynamically as well as hydrodynamically. The following discussion will, however, be made purely from the hydrodynamical standpoint, on the assumption that sea water is of uniform density. Even though this mathematical simplification has been employed, the author feels that the results obtained are consistent with observed phenomena.

It has been noticed that upwelling occurs most favorably when, in the northern (southern) hemisphere, a wind blows in such a manner that the coast is on the left-hand (right-hand) side of an observer who looks in the direction of the wind. Thus, upwelling off the coast of California is most noticeable in early summer when northwesterly winds prevail for several weeks nearly parallel to the coast.

In this investigation the effect of the Earth's rotation and the frictional forces due to both vertical and lateral mixing are taken into account. It should be stressed that horizontal mixing seems to play the most important role in the process of upwelling.

Theory of upwelling produced by a wind parallel to the coast--Consider a straight coast coincident with the axis of y, and take the x-axis perpendicular to it in the offshore direction (Fig. 1). Suppose a wind of constant force and direction is blowing steadily in a belt of limited width L parallel to the coast from negative to positive direction of y. This is a disposition favorable for the upwelling to occur actually. Take the z-axis vertically downwards.

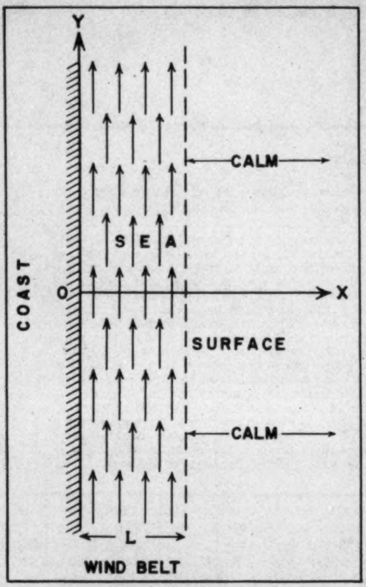


Fig. 1--Schematic diagram of wind to coast relationship for the development of upwelling in the northern hemisphere

If a constant wind blows for a sufficiently long period, a steady condition is attained in which the motion of water is independent of time. We assume that the wind stress cannot vary in the y-direction, but may be a function of x. This means that all the vertical and horizontal components of currents can be determined as functions of x and z only. Moreover, the surface of the sea will not be a plane, but will have a slope in the x-direction. In such a case, the hydrodynamical equations of motion are, after several reasonable simplifications

$$\left.\begin{array}{c}(A_h/\rho)\,\partial^2u/\partial x^2 + (A_v/\rho)\,\partial^2u/\partial z^2\\ + 2\,\omega\,\sin\phi\,v - g\,\partial\zeta/\partial x = 0\\ (A_h/\rho)\,\partial^2v/\partial x^2 + (A_v/\rho)\,\partial^2v/\partial z^2\\ - 2\,\omega\,\sin\phi\,u = 0\end{array}\right\}\ \ldots(1)$$

where u and v are the horizontal components of the current velocity in the x- and y-directions, ζ the surface elevation depending on x only, ρ the density, A_v and A_h the coefficients of vertical and horizontal mixing of sea water, ω the angular velocity of the Earth and ϕ the geographic latitude. In addition to these, we have the equation of continuity in the form

$$\partial u/\partial x + \partial w/\partial z = 0\ \ldots\ldots\ (2)$$

since $\partial v/\partial y = 0$. Here w is the vertical component of currents and represents the intensity of the upwelling.

Suppose the wind blows in the positive direction of y in a belt between the coast x = 0 and x = L. The conditions to be satisfied on the surface of the sea are therefore

$$z = 0\ \left\{\begin{array}{rl} -A_v\,\partial u/\partial z = 0 & \\ -A_v\,\partial v/\partial z = \tau & \text{for}\quad 0 \leqq x \leqq L\\ = 0 & \text{for}\quad L \leqq x < \infty\end{array}\right\}\ \ldots\ldots\ldots\ldots\ (3)$$

where τ is the stress of wind and may be either a constant or a function of x. On the bottom z = h we must have

$$z = h \qquad u = v = 0\ \ldots\ldots\ldots\ldots\ldots\ (4)$$

because of vertical friction. Along the coast which is considered to consist of vertical cliffs

$$x = 0 \qquad u = v = 0\ \ldots\ldots\ldots\ldots\ldots\ (5)$$

because of horizontal friction. In the region very far from both the coast and wind region, we have

$$x = \infty \qquad u = v = \partial\zeta/\partial x = 0\ \ldots\ldots\ldots\ldots\ (6)$$

Let us define D_v and D_h by

$$D_v = \pi\sqrt{A_v/\rho\,\omega\,\sin\phi} \qquad D_h = \pi\sqrt{A_h/\rho\,\omega\,\sin\phi}\ \ldots\ldots\ldots\ (7)$$

D_v is the depth of frictional influence defined by EKMAN [1905] in his theory of ocean currents, and D_h is a quantity having a dimension of a length and which may be called "frictional distance." This is a measure of the horizontal turbulence.

Thus (1) now becomes

$$\left.\begin{aligned} \partial^2 u/\partial\xi^2 + D_v^2\,\partial^2 u/\partial z^2 + 2\pi^2 v - (\pi^2 g/\omega\sin\phi)\,\partial\zeta/\partial\xi = 0 \\ \partial^2 v/\partial\xi^2 + D_v^2\,\partial^2 v/\partial z^2 - 2\pi^2 u = 0 \end{aligned}\right\} \qquad (8)$$

where

$$\xi = x/D_h \qquad (9)$$

In order to solve (8), suppose [TAKEGAMI, 1934]

$$u = (2/\pi)\int_0^\infty u_1(\lambda)\sin\lambda\xi\,d\lambda \qquad u_1(\lambda) = \int_0^\infty u(\alpha, z)\sin\lambda\alpha\,d\alpha \qquad (10)$$

$$v = (2/\pi)\int_0^\infty v_1(\lambda)\sin\lambda\xi\,d\lambda \qquad v_1(\lambda) = \int_0^\infty v(\alpha, z)\sin\lambda\alpha\,d\alpha \qquad (11)$$

$$\partial\zeta/\partial\xi = (2/\pi)\int_0^\infty \gamma(\lambda)\sin\lambda\xi\,d\lambda \qquad \gamma(\lambda) = \int_0^\infty (\partial\zeta/\partial\alpha)\sin\lambda\alpha\,d\alpha \qquad (12)$$

Next assume for the wind stress

$$-A_v\,\partial v/\partial z = (2/\pi)\int_0^\infty T(\lambda)\sin\lambda\xi\,d\lambda \qquad (13)$$

and

$$T(\lambda) = \int_0^\infty (-A_v\,\partial v/\partial\alpha)\sin\lambda\alpha\,d\alpha = \int_0^{L/D_h} \tau\sin\lambda\alpha\,d\alpha = [1 - \cos(\lambda L/D_h)]\,\tau/\lambda \qquad (14)$$

If τ is independent of x, substituting (10), (11), and (12) into (8) and writing

$$u_1 + i v_1 = \overline{W} \qquad (15)$$

the two equations of (8) are combined into

$$D_v^2\,d^2\overline{W}/dz^2 - (\lambda^2 + 2\pi^2 i)\,\overline{W} - (\pi^2 g/\omega\sin\phi D_h)\,\gamma(\lambda) = 0 \qquad (16)$$

and the conditions to be satisfied along the boundaries now become

$$-A_v\,d\overline{W}/dz\,\Big|_{z=0} = [1 - \cos(\lambda L/D_h)]\,i\tau/\lambda \qquad (17)$$

and

$$\overline{W}\,\Big|_{z=h} = 0 \qquad (18)$$

The solution of (16) subject to conditions (17) and (18) is

$$\begin{aligned} \overline{W} = &-[\pi^2 g\gamma(\lambda)/(\lambda^2 + 2\pi^2 i)\omega\sin\phi D_h]\left\{1 - [\cosh(\sqrt{\lambda^2 + 2\pi^2 i}\,z/D_v)]/[\cosh(\sqrt{\lambda^2 + 2\pi^2 i}\,h/D_v)]\right\} \\ &+[(i\tau D_v/A_v)/\sqrt{\lambda^2 + 2\pi^2 i}\,]\left\{\sinh[\sqrt{\lambda^2 + 2\pi^2 i}\,(h-z)/D_v]\right\}\left\{[1 - \cos(\lambda L/D_h)]/\lambda\right\}/[\cosh(\sqrt{\lambda^2 + 2\pi^2 i}\,h/D_v)] \end{aligned} \qquad (19)$$

If we separate the real part P of $\sqrt{\lambda^2 + 2\pi^2 i}$ from the imaginary part Q, we have

$$P = +\sqrt{(\sqrt{\lambda^4 + 4\pi^4} + \lambda^2)/2} \qquad Q = +\sqrt{(\sqrt{\lambda^4 + 4\pi^4} - \lambda^2)/2} \qquad (20)$$

Thus the real part of $\sqrt{\lambda^2 + 2\pi^2 i}$ is always greater than π. Hence, if the depth of the sea is sufficiently large ($h/D_v > 2$), (19) can be given very accurately by

$$\overline{W} = - [\pi^2 g \gamma(\lambda)/(\lambda^2 + 2\pi^2 i)\omega \sin\phi D_h] [1 - e^{-\sqrt{\lambda^2+2\pi^2 i}\,(h-z)/D_v}]$$

$$+ (i\tau D_v/A_v)(1/\sqrt{\lambda^2 + 2\pi^2 i})\, e^{-\sqrt{\lambda^2+2\pi^2 i}\, z/D_v} [1 - \cos(\lambda L/D_v)]/\lambda \quad \ldots\ldots\ldots (21)$$

In a steady state we do not have any vertical motion on the surface and bottom of the sea. We have, therefore

$$\overline{W} = 0 \qquad \text{for} \qquad z = 0 \text{ and } h \quad \ldots\ldots\ldots (22)$$

Integrating (2) with respect to z from the surface down to the bottom, we have

$$(\partial/\partial x)\int_0^h u dz = -w \Big|_{z=0}^{z=h} = 0$$

This means that the integral $\int_0^h u dz$ is independent of x, or therefore a constant. But as this integral must vanish directly on the coast or at $x = 0$, we must have

$$\int_0^h u dz = 0 \quad \ldots\ldots\ldots (23)$$

always. Integrating (21) with respect to z from 0 to h and equating the real part of the resulting equation to zero, we have

$$\gamma(\lambda) = \left\{(\pi^2\tau/\rho\omega)/(\lambda^2/2\pi^2)[h - PD_v/(P^2 + Q^2) + QD_v/(P^2 + Q^2)]\right\} [1 - \cos(\lambda L/D_h)]/\lambda \quad \ldots (24)$$

This determines the relation between the wind stress τ and the slope of the sea surface induced by the former. Substitution of (24) in (21) gives u_1 and v_1. Substitutions of u_1 and v_1 thus obtained and (24) into (10), (11), and (12) give the horizontal components u and v, and the surface slope $\partial\zeta/\partial\xi$. The vertical component w of motion can be derived from the equation of continuity (2) as

$$w = -(\partial/\partial x)\int_0^z u dz \quad \ldots\ldots\ldots (25)$$

Upwelling in a deep sea--When the sea is sufficiently deep and the ratio h/D_v increases indefinitely, we have from (24)

$$\gamma(\lambda) \rightarrow 0 \quad \ldots\ldots\ldots (26)$$

and (21) becomes

$$\overline{W} = [(i\tau D_v/A_v)/\sqrt{\lambda^2 + 2\pi^2 i}]\, e^{-\sqrt{\lambda^2+2\pi^2 i}\, z/D_v} [1 - \cos(\lambda L/D_h)]/\lambda \quad \ldots\ldots (27)$$

The components of velocity are then given by

$$u(x,z) = (2\pi\tau/\rho\omega \sin\phi D_v)\int_0^\infty G(\lambda,z)\, R(\lambda,x)\, d\lambda \quad \ldots\ldots\ldots (28)$$

$$v(x,z) = (2\pi\tau/\rho\omega \sin\phi D_v)\int_0^\infty H(\lambda,z)\, R(\lambda,x)\, d\lambda \quad \ldots\ldots\ldots (29)$$

$$w(x,z) = (2\pi\tau/\rho\omega \sin\phi D_v)(D_h/D_v)\int_0^\infty L(\lambda,z)\, S(\lambda,x)\, d\lambda \quad \ldots\ldots\ldots (30)$$

where

$$G(\lambda, z) = \left\{[Q\cos(Qz/D_v) + P\sin(Qz/D_v)]/(P^2 + Q^2)\right\} e^{-Pz/D_v} \quad \ldots\ldots\ldots\ldots\ldots (31)$$

$$H(\lambda, z) = \left\{[P\cos(Qz/D_v) - Q\sin(Qz/D_v)]/(P^2 + Q^2)\right\} e^{-Pz/D_v} \quad \ldots\ldots\ldots\ldots\ldots (32)$$

$$L(\lambda, z) = \left\{2PQ\,[\cos(Qz/D_v)\, e^{-Pz/D_v} - 1] + (P^2 - Q^2)\sin(Qz/D_v)\, e^{-Pz/D_v}\right\}/(P^2 + Q^2)^2 \quad \ldots (33)$$

$$R(\lambda, x) = \sin(\lambda x/D_h)\,[1 - \cos(\lambda L/D_h)]/\lambda \quad \ldots\ldots\ldots\ldots\ldots\ldots (34)$$

$$S(\lambda, x) = \cos(\lambda x/D_h)\,[1 - \cos(\lambda L/D_h)]/1 \quad \ldots\ldots\ldots\ldots\ldots\ldots (35)$$

and P and Q are the real and imaginary parts of $\sqrt{\lambda^2 + 2\pi^2 i}$ whose expressions are given by (20).

These results show that owing to the effect of the wind blowing parallel to the coast, a vertical circulation in the plane perpendicular to the coast can be expected in addition to a coastal current parallel to the wind direction. The vertical component of this circulation evidently represents the upwelling. However, the upwelling must be ascending currents close to the coast. We sometimes have descending currents on the coast produced by an onshore wind as described by LONGARD and BANKS [1952]. But such descending currents will be excluded from our discussion because they do not bring cold and nutritious water from deeper layers.

From expressions (28), (29), and (30) for u, v, and w, it can be expected that the horizontal velocity of water in this process is approximately D_h/D_v or $\sqrt{A_h/A_v}$ times as large as the vertical velocity. This result will be very useful in estimating the approximate speed of upwelling.

If we define a function $\psi(x, z)$ as

$$\psi(x, z) = (2\pi\tau/\rho\omega\sin\phi)\ \Phi_y(x, z) = (2\pi\tau/\rho\omega\sin\phi) \times \text{real part of}$$

$$i\int_0^\infty \left\{[(e^{-\sqrt{\lambda^2+2\pi^2 i}\, z/D_v} - 1)/(\lambda^2 + 2\pi^2 i)]\right\}\left\{\sin(\lambda L/D_h)\,[1 - \cos(\lambda L/D_h)]/\lambda\right\} d\lambda \quad .. (36)$$

we can show that this is the stream-function in the plane perpendicular to the coast (xz-plane), and u and w are derived from this formula as

$$u = -\partial\psi/\partial z \qquad\qquad w = +\partial\psi/\partial x \quad \ldots\ldots\ldots\ldots\ldots (37)$$

so that any curve

$$\psi(x, z) = \text{constant}$$

will represent a streamline. If we draw such curves at a constant difference in $\psi(x, z)$, the velocity of the current is inversely proportional to the distance between two successive curves.

A numerical example--So far the author has elucidated the process of upwelling in a quantitative manner and obtained the expressions for the motion of water produced by a wind blowing parallel to the coast in a belt of finite width. The stream function $\psi(x, z)$ [$= (2\pi\tau/\rho\omega\sin\phi)\,\Phi_y$] can be computed from (36) for any distance x/D_h from the coast and any depth z/D_v below the surface. The results of computation for several values of x/D_h and z/D_v are given in Table 1 and illustrated by Figure 2. The figures in Table 1 should be multiplied by

$$(2\pi\tau/\rho\omega\sin\phi) \times 10^{-4} \quad \ldots\ldots\ldots\ldots\ldots\ldots (38)$$

The values of the stream function are all negative. This means that an upwelling develops close to the coast and that there is a motion of water in an offshore direction in the upper layers of the sea directly below the surface swept by wind. An intense upwelling can be seen within 0.5 D_h from the coast and the streamlines go down gradually outside the wind zone, meaning that the process of sinking occurs there.

The fact that the expressions for the velocity components all include $\sin\phi$ in the denominator shows that the lower the latitude the more intense will be the process of upwelling. Perhaps the strong upwelling off the Peruvian Coast may be ascribed to this theoretical result.

Table 1--Values of the stream function $\Phi_y (x, z) \times 10^4$

z/D_v	x/D_h								
	0	0.1396	0.2793	0.5585	0.8378	1.1170	1.3963	1.6755	1.9548
0	0	0	0	0	0	0	0	0	0
0.2	0	-175	-313	-449	-461	-465	-455	-425	-310
0.4	0	-277	-499	-725	-748	-750	-734	-682	-496
0.6	0	-321	-578	-843	-867	-866	-848	-788	-576
0.8	0	-334	-600	-871	-891	-887	-869	-808	-589
1.0	0	-332	-598	-865	-890	-873	-856	-797	-579
1.2	0	-329	-592	-852	-863	-853	-837	-782	-568
1.4	0	-327	-587	-844	-853	-843	-827	-773	-561
1.6	0	-326	-585	-840	-848	-837	-823	-769	-558

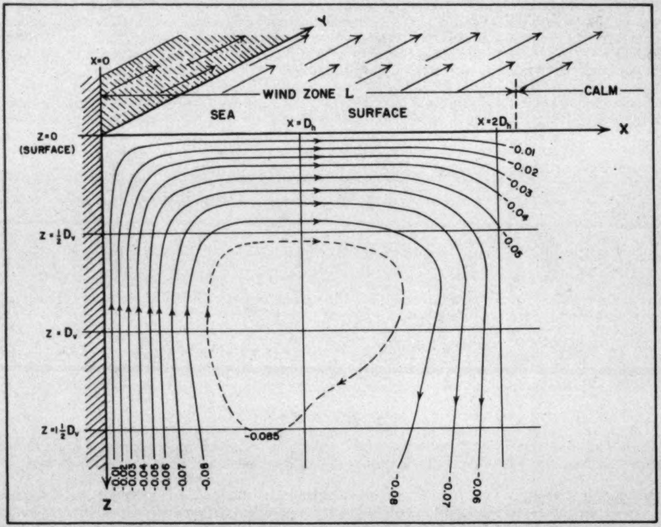


Fig. 2--Upwelling as induced by a wind parallel to the coast (illustrated by the streamlines in the vertical plane perpendicular to the coast)

It is interesting and useful to compute the magnitude of the offshore currents and the velocity of upwelling from the stream function (36) and to compare the result with those formerly estimated from various sources.

It is of course not easy to estimate the magnitude of the coefficients of mixing. The vertical mixing coefficient D_v may be estimated at something like 1000 cgs. If we adopt this value, D_v is about 162 m for a latitude of 30°N. To estimate A_h is even more difficult. But actual oceanographic observations show that $A_h/A_v = 10^6$ approximately. This means that D_h is just about 1000 times as large as D_v, or 162 km. Furthermore, we do not know much about the width of the coastal wind belt. In this computation, the author tentatively assumed $L = 2.0944\, D_h$, that is about twice as large as D_h, or 339 km.

It is still more difficult to estimate the wind velocity of the northwesterlies prevailing off the coast of Southern California in the earlier summer months. The author took $\tau = 1$ cgs. This corresponds to a wind velocity between five and six meters per second. If we consider the upwelling off the coast of Southern California, taking $\phi = 30°N$, we have

$$2\pi\tau/\rho\omega \sin\phi = 2.37 \times 10^5 \text{ sec}^{-1}$$

From Table 1 we can compute the average velocity between the surface and the layer $0.2\ D_v$ deep by

$$-(2\pi\tau/\rho\omega \sin\phi)\ \Delta\psi/\Delta z = +2.37 \times 10^5 \times 0.045/0.2\,D_v = 3.35 \text{ cm/sec (offshore)}$$

This is the maximum velocity of the offshore current in the layer between the surface and approximately 32.4 m.

The maximum upwelling velocity can be estimated in a similar manner, namely, at

$$(2\pi\tau/\rho\omega \sin\phi)\ (\Delta\psi/\Delta x) = -2.37\times10^5\times0.033/0.14\,D_h = -3.14\times10^{-3} \text{ cm/sec} = 2.7 \text{ m/day upward}$$

This speed of upwelling is approximately 80 m/month. McEWEN [1929] estimated the speed of upwelling off the coast of Southern California at 10 to 20 m/month. From SVERDRUP's [1938] diagrams showing the distribution of isopycnals observed at an interval of 38 days, SAITO [1951] obtained 2.25 m/day or about 80 m/month for the upwelling velocity off Southern California. The present result appears to show a speed a little too high, but may be suggestive of the order of magnitude of ascending motion in the process of upwelling.

From the diagram in Figure 2, we can see that the water mass participating in this process of upwelling comes from the layers from $z = D_v$ to $1.5\,D_v$ or more. If we take $D_v = 162$ m, the layers from which the upwelled water originates are located somewhere around 200 m or deeper. This also agrees with the estimation derived from the results of oceanographic observations off the coast of Southern California [SVERDRUP and Others, 1942].

Upwelling due to a wind not parallel to the coast--In the foregoing discussion the author has shown the possibility of upwelling induced by a wind parallel to the coast. It may be anticipated that a similar motion can occur in the same vertical plane as a result of an offshore wind, that is, a wind blowing offshore at right angles to the coast. By a study of a combination of these two motions, it should be possible to determine what kind of vertical water motion would correspond to a wind of given direction. In the following lines, a method will be given by which we can determine the most favorable wind direction for upwelling.

Let us examine a wind which is not perpendicular to the coast and divide the wind stress τ into its two components τ_x and τ_y in the x- and y-directions (Fig. 3). Then the surface condition to be satisfied by u and v should be written, in place of (17)

$$\left.-A_v\,(\partial/\partial z)\,(u + iv)\right|_{z=0} \left.\begin{aligned} &= \tau_x + i\tau_y && (0 \leqq x \leqq L) \\ &= 0 && (L < x < \infty) \end{aligned}\right\} \quad \ldots\ldots\ (39)$$

while the dynamical equations, equation of continuity, and other boundary conditions remain the same.

In a manner similar to that used in our foregoing discussion, we can integrate the equations of motion. The stream function $\psi(x, z)$ in the plane perpendicular to the coast (xz-plane) and the horizontal components of current velocity are given by

$$\psi(x,z) = \text{real part of } [2\pi\,(\tau_x + i\tau_y)/\rho\omega \sin\phi] \int_0^\infty [(e^{-\sqrt{\lambda^2+2\pi^2 i}\,z/D_v} - 1)/(\lambda^2 + 2\pi^2 i)]$$

$$\left\{\sin(\lambda x/D_h)\ [1 - \cos(\lambda L/D_h)]/\lambda\right\} d\lambda \quad \ldots\ldots\ldots\ldots\ldots\ldots\ (40)$$

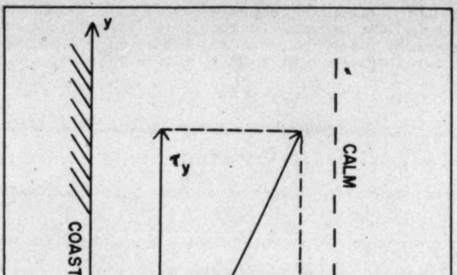


Fig. 3--Wind making an angle θ with the coast

and

$$u + iv = [2\pi(\tau_x + i\tau_y)/\rho\omega \sin\phi] \int_0^\infty [e^{-\sqrt{\lambda^2+2\pi^2 i}\, z/D_v} / \sqrt{\lambda^2 + 2\pi^2 i}] \left\{\sin(\lambda x/D_h)\,[1 - \cos(\lambda L/D_h)]/\lambda\right\} d\lambda \qquad (41)$$

or, in real forms

$$\psi(x,z) = (2\pi\tau_x/\rho\omega \sin\phi)\,\Phi_x(x,z) + (2\pi\tau_y/\rho\omega \sin\phi)\,\Phi_y(x,z) \qquad (42)$$

$$u(x,z) = (2\pi\tau_x/\rho\omega \sin\phi D_v)\,N(x,z) - (2\pi\tau_y/\rho\omega \sin\phi D_v)\,M(x,z) \qquad (43)$$

$$v(x,z) = (2\pi\tau_x/\rho\omega \sin\phi D_v)\,M(x,z) + (2\pi\tau_y/\rho\omega \sin\phi D_v)\,N(x,z) \qquad (44)$$

where

$$\Phi_x(x,z) = \int_0^\infty \left\{(P^2 - Q^2)\,[e^{-Pz/D_v} \cos(Qz/D_v) - 1] - 2PQ\,e^{-Pz/D_v} \sin(Qz/D_v)\right\}/(P^2 + Q^2)^2 \times \left\{\sin(\lambda x/D_h)\,[1 - \cos(\lambda L/D_h)]/\lambda\right\} d\lambda \qquad (45)$$

$$\Phi_y(x,z) = \int_0^\infty \left\{(P^2 - Q^2)\, e^{-Pz/D_v} \sin(Qz/D_v) + 2PQ\,[e^{-Pz/D_v} - 1]\right\}/(P^2 + Q^2)^2 \times \left\{\sin(\lambda x/D_h)\,[1 - \cos(\lambda L/D_h)]/\lambda\right\} d\lambda \quad \ldots\ldots (46)$$

$$M(x,z) = \int_0^\infty \left\{[Q\cos(Qz/D_v) + P\sin(Qz/D_v)]/(P^2 + Q^2)\right\} e^{-Pz/D_v} \left\{\sin(\lambda x/D_h)\,[1 - \cos(\lambda L/D_h)]/\lambda\right\} d\lambda \quad \ldots\ldots (47)$$

$$N(x,z) = \int_0^\infty \left\{[P\cos(Qz/D_v) - Q\sin(Qz/D_v)]/(P^2 + Q^2)\right\} e^{-Pz/D_v} \left\{\sin(\lambda x/D_h)\,[1 - \cos(\lambda L/D_h)]/\lambda\right\} d\lambda \quad \ldots\ldots (48)$$

Thus the stream function is composed of two components, that is, those due to the wind stress τ_x perpendicular, and τ_y parallel to the coast.

If we put

$$\tau_x = 0 \qquad \text{and} \qquad \tau_y = \tau$$

we have exactly the foregoing discussion in which the wind blows parallel to the coast.

The component stream functions $\Phi_x(x, z)$ and $\Phi_y(x, z)$, and the functions $M(x, z)$ and $N(x, z)$, which give the horizontal components of velocity, are evaluated numerically against several values of x/D_h and z/D_v, and are compiled in Tables 1 to 4.

Table 2--Values of the stream function $\Phi_x(x, z) \times 10^4$

z/D_v	x/D_h								
	0	0.1396	0.2793	0.5585	0.8378	1.1170	1.3963	1.6755	1.9548
0	0	0	0	0	0	0	0	0	0
0.2	0	-168	-303	-301	-254	-270	-280	-305	-202
0.4	0	-194	-342	-310	-230	-238	-257	-303	-199
0.6	0	-179	-309	-234	-135	-135	-161	-226	-133
0.8	0	-162	-275	-172	- 68	- 58	- 83	-162	- 85
1.0	0	-152	-256	-138	- 19	- 17	- 43	-129	- 61
1.2	0	-148	-248	-125	- 5	- 3	- 30	-107	- 54
1.4	0	-148	-274	-124	- 4	- 3	- 30	-107	- 54
1.6	0	-147	-248	-126	- 6	- 6	- 33	-110	- 57

Table 3--Values of the function $N(x, z) \times 10^3$

z/D_v	x/D_h								
	0	0.1396	0.2793	0.5585	0.8378	1.1170	1.3963	1.6755	1.9548
0	0	+240	+277	+284	+253	+252	+252	+266	+243
0.2	0	+ 41	+ 64	+ 55	+ 35	+ 31	+ 38	+ 47	+ 22
0.4	0	- 3	- 8	- 28	- 42	- 45	- 42	- 28	- 17
0.6	0	- 10	- 20	- 38	- 47	- 50	- 48	- 39	- 29
0.8	0	- 7	- 14	- 24	- 29	- 30	- 29	- 24	- 20
1.0	0	- 3	- 6	- 11	- 12	- 12	- 12	- 10	- 8
1.2	0	- 1	- 2	- 2	- 3	- 3	- 2	- 2	- 1
1.4	0	0	0	- 1	+ 1	+ 1	+ 1	+ 1	+ 1
1.6	0	0	+ 1	+ 1	+ 2	+ 2	+ 2	+ 1	+ 1

Table 4--Values of the function $M(x, z) \times 10^3$

z/D_v	x/D_h								
	0	0,1396	0.2793	0.5585	0.8378	1.1170	1.3963	1.6755	1.9548
0	0	-98	-174	-248	-255	-243	-263	-235	-174
0.2	0	-70	-127	-186	-191	-182	-197	-175	-129
0.4	0	-34	- 62	- 93	- 96	- 90	- 97	- 85	- 62
0.6	0	-12	- 21	- 31	- 30	- 26	- 30	- 26	- 18
0.8	0	- 2	- 3	- 2	0	+ 3	+ 1	+ 1	+ 1
1.0	0	+ 1	+ 3	+ 6	+ 10	+ 30	+ 9	+ 8	+ 6
1.2	0	+ 1	+ 3	+ 6	+ 8	+ 8	+ 8	+ 6	+ 5
1.4	0	+ 1	+ 2	+ 3	+ 4	+ 4	+ 4	+ 3	+ 2
1.6	0	0	+ 1	+ 1	+ 1	+ 1	+ 1	+ 1	+ 1

Vertical circulation patterns--Figure 2 and 4 illustrate the contents of Tables 1 and 2 respectively. They show the streamlines in the vertical circulations induced in the plane perpendicular to the coast (xz-plane) by offshore and longshore winds. Both are clockwise circulations. The values of stream functions are all negative, showing that upwelling exists close to the coast produced by the wind stresses in positive directions of x and y. In each of these cases, the water is upwelled from levels deeper than $z = D_v$, but, as a whole, it appears that the upwelled water originates in deeper levels with a longshore than with an offshore wind. The circulation induced by a longshore wind has been described in detail in the foregoing discussion. But the circulation due to an offshore wind of the same stress will carry a much smaller amount of water than will that due to a longshore wind. Moreover, the former has a rather complicated structure, having two eddies (Fig. 4) in upper layers, one situated close to the coast, the other near the outer boundary of the wind belt. These circumstances mean that upwelling due to a longshore wind is far more effective in lowering the temperature of the region close to the coast than that induced by an offshore one, since the former brings a much larger amount of colder water to the surface from deeper levels than the latter.

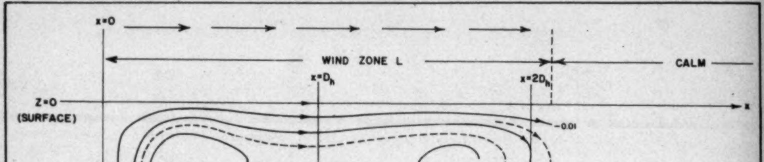


Fig. 4--Upwelling as induced by an offshore wind

Most favorable wind direction for upwelling--The amount T of water upwelled through a long horizontal strip one cm wide and extending from the coast to a distance x will be evaluated by

$$T = \int_0^x \rho w dx = \rho \int_0^x (\partial\psi/\partial x) dx = \rho\psi(x, z) - \rho\psi(0, z) = \rho\psi(x, z)$$

since the stream function vanishes along the coastal wall (x = 0). Thus the vertical mass transport T will be largest when we take x at a distance at which Φ_x and Φ_y have the largest negative values. By inspection of Tables 1 and 2 and Figures 2 and 4, we can estimate

$$\left.\begin{array}{ll} T_y = -0.090(2\pi\tau_y/\rho\omega\sin\phi) & \text{by longshore wind, and} \\ T_x = -0.0355(2\pi\tau_x/\rho\omega\sin\phi) & \text{by offshore wind} \end{array}\right\} \ldots\ldots\ldots (49)$$

If the wind blows in an offshore direction making an angle θ with the coast (Fig. 3), we have

$$\tau_x = \tau\sin\theta \qquad \tau_y = \tau\cos\theta \ldots\ldots\ldots\ldots\ldots\ldots (50)$$

where τ is the absolute magnitude of the wind stress. Then we have from (49)

$$T = T_x + T_y = (-0.0355\sin\theta - 0.090\cos\theta)\ 2\pi\tau/\omega\sin\phi \ldots\ldots\ldots\ldots (51)$$

This gives an approximate amount of water upwelled to the upper layers per unit length of the coast. The most intense upwelling will therefore take place when $dT/d\theta = 0$, or

$$\tan\theta = -0.0355/-0.090 \quad \text{or} \quad \theta = 21^\circ.5 \ldots\ldots\ldots\ldots\ldots (52)$$

providing the magnitude of the wind stress remains the same. This result means that upwelling will be most intense when the wind direction makes an angle of 21°.5 with the coast line in an offshore direction, that is, when it is slightly deviated offshore from the coast line. This angle of deviation will of course depend upon the width L of the wind belt. But for a value L exceeding D_h, it is understood that θ approaches an asymptotic value not much different from 21°.5. According to Arnold Glaser, upwelling off the coast of Lima, Peru, appears to be most intense when the southerlies blow in a slight offshore direction rather than when they blow parallel to the coast.

In the Gulf of Mexico, we have easterlies almost all year round. This means that we can always expect upwelling along the northern coast of Cuba and the Yucatan Coast of Mexico. We have some evidence of upwelling or existence of colder water off these coasts [SMITH and Others, 1951], and we know that many American vessels fish in the waters off the Yucatan Coast. This fact may suggest the existence of upwelling in this region. According to the surface observations of the Department of Oceanography, Agricultural and Mechanical College of Texas, made recently, there are some indications of colder surface water in the western part of the Gulf of Mexico very close to the coasts. If these conditions really exist, this temperature distribution may be ascribed to upwelling due to the easterly winds prevailing in these latitudes.

Coastal currents--Recently a number of observations [PUTNAM and Others, 1949; SHEPARD and INMAN, 1950, 1951; INMAN and QUINN, 1953] on the flow of water close or adjacent to coasts have been reported. Many authors have discussed this subject, but they have not yet been able to arrive at a satisfactory explanation of possible causes of coastal or longshore currents. However, most of these currents are ascribed to the action of surf and waves. The longshore component which we have obtained may explain some part of these flows. The expression for this component is given by

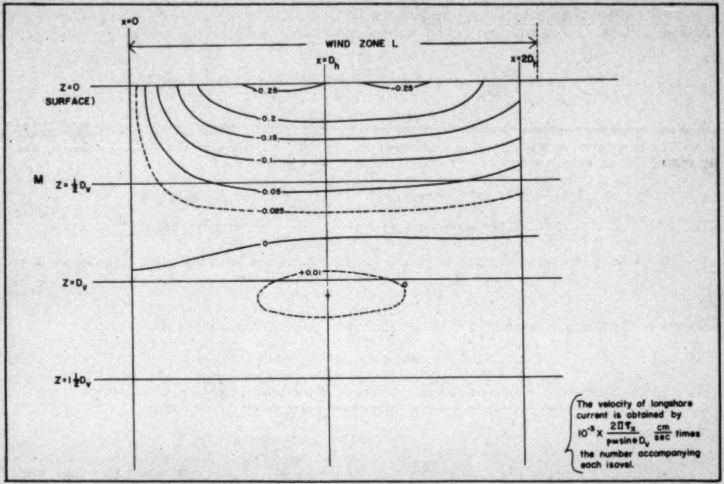
$$v(x,z) = (2\pi\tau_x/\rho\omega\sin\phi D_v)\ N(x,z) - (2\pi\tau_y/\rho\omega\sin\phi D_v)\ M(x,z) \ldots\ldots\ldots (53)$$

where M and N are the functions compiled in Tables 3 and 4 and illustrated in Figures 5 and 6. The two terms in the right-hand member of (53) show the longshore currents induced by offshore and longshore winds respectively. If the wind is parallel to the coast, we have $\tau_x = 0$ and have

$$v = -(2\pi\tau_y/\rho\omega\sin\phi D_v)\ M(x,z) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (54)$$

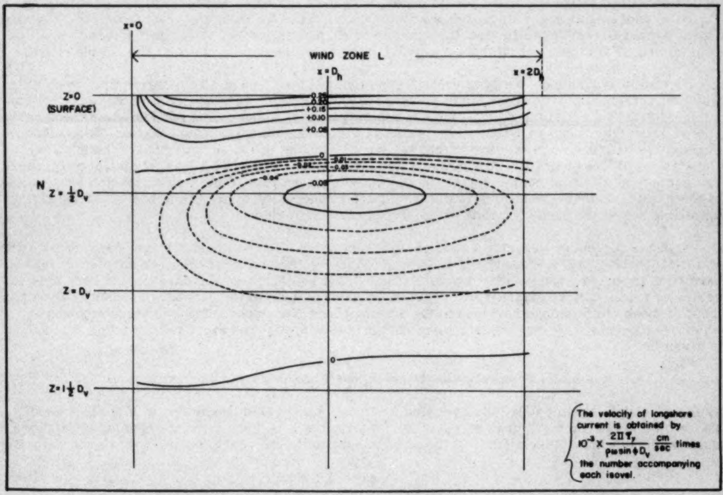
and if it is blowing in an offshore direction perpendicular to the coast, we have

$$v = +(2\pi\tau_x/\rho\omega\sin\phi D_v)\ N(x,z) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (55)$$



The velocity of longshore current is obtained by $10^{-3} \times \frac{2\Pi\tau_x}{\rho\omega\sin\phi D_v}\frac{cm}{sec}$ times the number accompanying each isovel.

Fig. 5--Distribution of longshore currents M (x, z) induced by a wind τ_x parallel to the coast



The velocity of longshore current is obtained by $10^{-3} \times \frac{2\Pi\tau_y}{\rho\omega\sin\phi D_v}\frac{cm}{sec}$ times the number accompanying each isovel.

Fig. 6--Distribution of longshore currents N (x, z) induced by an offshore wind τ_y

From Tables 3 and 4, and Figures 5 and 6 it is possible for us to tell the difference between the two cases. The coastal current induced by a longshore wind is directed leeward as far down as the level $z = 0.9\,D_v$, but the direction of flow is reversed at deeper levels. On the other hand, the longshore current produced by an offshore wind flows to the right of the wind direction in layers shallower than $z = 0.3\,D_v$ only. There is a secondary maximum of velocity in the opposite direction at the approximate level $z = 0.5\,D_v$.

Vertical variation of horizontal currents; Ekman spiral--The expressions

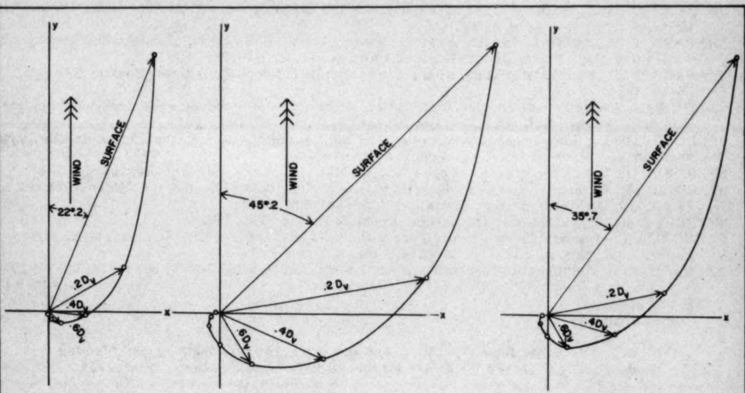
$$\left.\begin{aligned} u(x, z) &= (2\pi\tau_x/\rho\omega \sin\phi D_v)\, N(x, z) - (2\pi\tau_y/\rho\omega \sin\phi D_v)\, M(x, z) \\ v(x, z) &= (2\pi\tau_x/\rho\omega \sin\phi D_v)\, M(x, z) + (2\pi\tau_y/\rho\omega \sin\phi D_v)\, N(x, z) \end{aligned}\right\} \ldots\ldots (56)$$

for the horizontal currents show that the angle between the wind and the current induced at a given depth depends only upon the distance from the coast and not on the direction of wind. The angle between the wind and the surface current induced by it is computed for several different distances from the coast and compiled in Table 5.

Table 5--The angle between the wind and surface current

x/D_h	0	0.1396	0.2793	0.5585	0.8378	1.1170	1.3963	1.6755	1.9548
Angle	0°	22°.2	32°.2	41°.2	45°.2	44°.3	46°.3	41°.5	35°.7

Thus the angle between the wind and surface current is near 45° at the middle part of the wind belt, but decreases both toward the coast and toward the outer margin of the wind belt. Along the coast there is a very weak current in approximately the same direction as the wind. The vertical variation of currents is practically equal to the EKMAN [1905] spiral along the median line of the wind belt, but is more or less flattened close to the coast and near the outer margin of the wind belt. Some of these spirals are illustrated in Figure 7.



$\frac{x}{D_h} = .1396$ (CLOSE TO THE COAST)

$\frac{x}{D_h} = .8378$ (MIDDLE PART OF WIND BELT)

$\frac{x}{D_h} = 1.9548$ (CLOSE TO OUTER PART OF WIND BELT)

Fig. 7--Vertical variation of drift currents

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USE OF SMALL-SCALE EXPERIMENTS WITH EQUILIBRIUM PROFILES IN STUDYING ACTUAL PROBLEMS AND DEVELOPING PLANS FOR COASTAL PROTECTION

Per Bruun

Abstract--Examples from the Danish coasts demonstrate the applicability of small scale laboratory experiments with equilibrium beach profiles to interpreting observed conditions on beaches and predicting performance of coastal protection structures.

Definition of equilibrium beach profiles--(Laboratory) An equilibrium beach profile is a beach profile which maintains its form. The initial condition is a vertical wall. (Actual) An equilibrium beach profile is a statistical average profile which maintains its form apart from smaller fluctuations including seasonal fluctuations. One must distinguish between a "summer" profile and a "winter" profile.

Actual beach profiles--The form of the actual beach profile depends on such factors as wave characteristics and their mutual ratios, direction of wave propagation, and change in wave action. Different waves, for instance, try to destroy the system of bars not belonging to their peculiar profile and build up a new system of bars. It must also be assumed that the profile is a function of grain size, grain-size distribution, and specific gravity. Where bed rock exists, bars cannot be formed. In addition, the coastal currents, especially the longshore current due to the wave breaking, may play a role.

Ultimately the form depends on the initial conditions. On very steep coasts a single bar may appear, or perhaps none at all. It seems as if the number of bars depends on the magnitude of littoral drift. When the drift increases, the possibility of formation of bars will also increase, but it cannot be maintained that a profile with, for instance, three bars carries more material than a profile with only one bar, because many other factors may influence the magnitude of littoral drift.

Considerations on the basis of the development of beach profiles on the Danish North Sea coast, which is built up of sand with grain size 0.2 to 0.3 mm, seem to show that one can distinguish between profiles in another way; that is, between the over-nourished, the sufficiently-nourished, and the under-nourished profiles [BRUUN, 1951].

The over-nourished profiles are fed with more material than the waves can shape into a beach profile. These, therefore, are irregular and often perform as irregular shoals. On the Danish North Sea coast we have some examples of such profiles in the extreme areas at the Skaw to the north and at Blaavands Huk to the south (Fig. 1). In both cases the littoral drift is at a maximum, and accumulations take place irregularly [BRUUN, 1953].

There are two different types of sufficiently-nourished profiles. At one of them the profiles are not fed with more material than the waves can shape into a profile having the same "equilibrium form." At the other, the loss of material equals the supply of material and the profile has still the same equilibrium form. The beach profiles off Ringkøbing Inlet Barrier (Fig. 1) are probably of that kind.

The under-nourished beach profiles are eroded, that is, the coastline retrogrades. Profiles of that kind are found between Lodbjaerg and Nørre Lyngvig. The under-nourished beach profiles will always keep an equilibrium form, but the form may change from one locality to another, depending on the conditions in general as mentioned above.

Figure 2 shows a beach profile at Lyngby in 1876 and 1938. This profile, under-nourished to a smaller degree, has only one bar and is situated close to the nodal point for the near-shore littoral drift on the North Sea coast, which seems to be the coast area between Lodbjaerg and Lyngby [BRUUN, 1953]. Figure 3 shows the beach profile at the Old Skaw. This profile is under-nourished, the retrogradation of the shoreline being about three feet per year, but the littoral drift is very considerable [BRUUN, 1953].

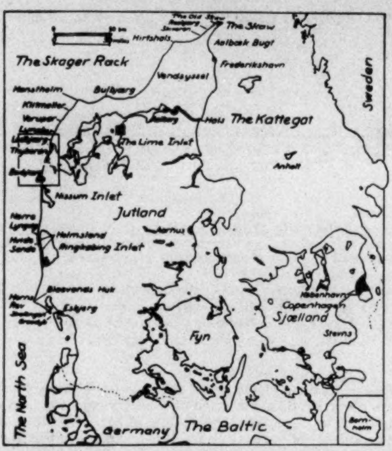
The Old Skaw
Skagen
The Skaw
Hirtshals
Aalbæk Bugt
The Skager Rack
Frederikshavn
Vendsyssel
Hanstholm
Bulbjerg
Klitmøller
Vorupør
Lyngby
Thyborøn
Harboøre
Sweden
Hals
The Kattegat
Aalborg
The Lime Inlet
Anholt
Nissum Inlet
Jutland
Nørre Lyngvig
Holmsland
Hvide Sande
Ringkøbing Inlet
Aarhus
Blaavands Huk
Horns Rev
Esbjerg
København
Copenhagen
Sjælland
Stevns
Fyn
The North Sea
Germany
The Baltic
Bornholm

Fig. 1--Map of Denmark, showing places mentioned in the text; the rectangle at the west entrance to the Lime Inlet (Limfjorden) is shown in larger scale in Figure 6

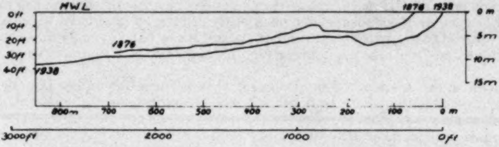

Fig. 2--Beach profiles at Lyngby on the Danish North Sea coast

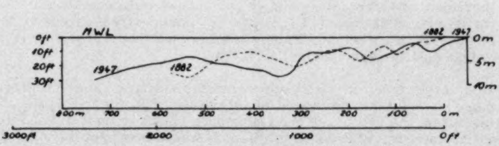

Fig. 3--Beach profiles at the Old Skaw (Gammel Skagen) at the northern tip of Jutland

From the above it seems that progradation of a coast may take place with or without equilibrium profiles, while retrogradation of a shoreline can only take place with equilibrium profiles having a maximum steepness corresponding to the quantity of littoral drift. This is the case on the Danish North Sea coast. An actual equilibrium profile, therefore, should be defined as a stable profile with maximum steepness (see the section below on fluctuations of beach profiles from one period to another).

Investigations on equilibrium profiles in the laboratory--Laboratory experiments have shown [BAGNOLD, 1940; BEACH EROSION BOARD, 1952; BRUUN, 1951; JOHNSON, 1949; and especially SAVILLE, 1950]:

(a) Waves with high steepness ratio produce a bar profile (Fig. 4a). Waves with low steepness ratio produce a beach ridge profile (Fig. 4c, 4d) [BRUUN, 1953].

(b) Waves with high steepness ratio erode the beach; waves with low steepness ratio build up the beach.

(c) Waves with high steepness ratio can be identified as winter waves. They form a storm or winter profile. Waves with low steepness ratio can be identified as summer waves. They build up a swell or summer profile. The intermediate profile occurs at a steepness ratio of about $H_0/L_0 = 0.026$ (Fig. 4b).

(d) There are two types of littoral drift, bed load transport on the beach itself (beach drift) due to uprush and backwash, and suspended load transport in the breaker zone due to the breaking waves and the generated longshore currents [SAVILLE, 1950].

(e) In equilibrium storm profiles, transport is mainly of material in suspension. In equilibrium swell profiles, transport is mainly beach drift. The transition between these different types of transport is sudden and occurs at a steepness ratio of about 0.03 [SAVILLE, 1950].

(f) The transport along summer profiles is much greater than that along winter profiles for waves with the same energy content. The peak transport occurs at a steepness ratio of from 0.02 to 0.025 and is almost entirely beach drift [SAVILLE, 1950].

(g) The transport rate decreases very rapidly for steepness ratios less than 0.02 [SAVILLE, 1950].

(h) The transport rate increases with an increase in wave energy, other conditions remaining the same [SAVILLE, 1950].

(i) The transport occurs almost entirely in the area shoreward from the breaker [SAVILLE, 1950].

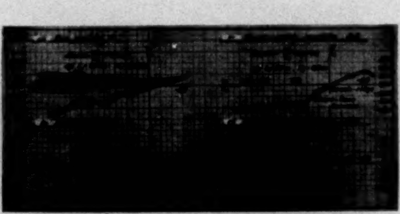

Fig. 4--Equilibrium profiles produced in laboratory experiments under various wave conditions

Investigations with actual beach profiles

Fluctuations in beach profiles from one season to another: short-period fluctuations--Investigations have been carried out in the United States and in Denmark [BEACH EROSION BOARD, 1952; BRUUN, 1953; SHEPARD and INMAN, 1950]. Figure 5 shows five profiles sounded about 330 ft apart. Simultaneous levels were taken of the beach itself. The soundings were carried out to the 30-ft depth contour about 3300 ft from the shoreline. For wind and wave conditions in the North Sea, see BRUUN [1953].

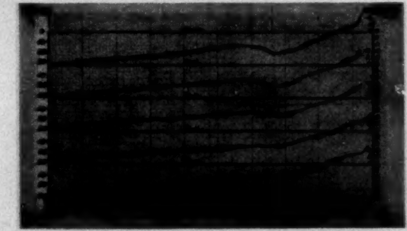

Fig. 5--Profiles on the Danish North Sea coast, south of Bovbjaerg, at the cross-hatched spot on Figure 1; dotted lines taken on Nov. 15, 1951; solid on Jan. 23, 1952; lines spaced 330 ft

The dotted lines show the profiles on November 15, 1951. The profiles are summer profiles with beach ridges on the beach itself. Although the bar has migrated toward the shoreline, it is still there, as the summer waves possibly should have acted for a much longer time to carry material from the bar to the beach.

The profiles from the soundings on January 23, 1952, are shown with full lines. Several severe gales occurred between November and January. It can be seen that the difference between the summer profile and the winter profile is that the summer profile has a beach ridge and at the same time is steeper than the winter profile.

The accumulations in the outer sections of the beach profiles must have been caused either by sand moving from the bottom outside the 30-ft depth or from a migrating sand wave on the bottom along the shore. Investigations in this respect are under execution.

Long-period fluctuations on the Danish North Sea coast along the Lime Inlet Barriers--The Lime Inlet Barriers (Fig. 6) are built up of sand from an elevation about +5 ft to elevation -19 ft. Below -19 ft a very soft clay deposited in the Inlet in the Litorina time is found. In Figure 6 are shown the positions of the shoreline in 1791, when the Barrier was unbroken, and today. The existing open channel was formed by a barrier breach in 1862. Several channels existed before that time,

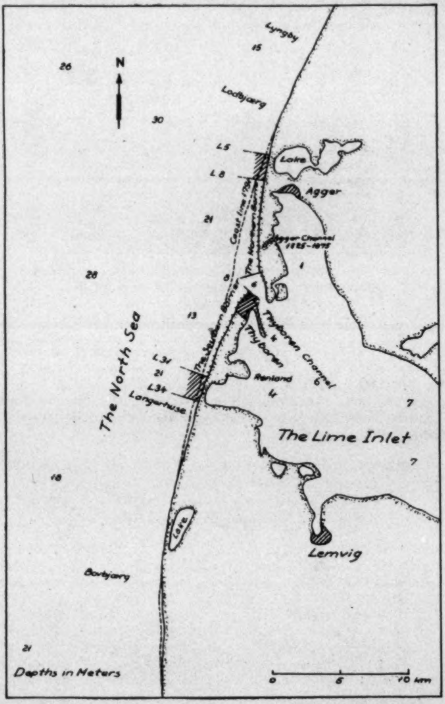
Lyngby
15
26
N
Lodbjerg
30
L5
L8
Lake
Agger
21
Coast line 1791
The Northern Barrier
Agger Channel
1825-1875
1
28
0
6
13
The Southern Barrier
Thyborøn
Thyborøn Channel
4
The North Sea
L31
21
L34
Langerhuse
Rønland
4
6
7
The Lime Inlet
7
18
Lake
Lemvig
Bovbjerg
21
Depths in Meters
0
5
10 km

Fig. 6--The Lime Inlet (Limfjorden) Barriers on the North Sea coast; the area covered by this figure is shown by a rectangle in Figure 1

for instance the Agger Channel, breached in 1825 and closed by nature in 1875. Historical accounts suggest that in the 11th century the Lime Inlet had an open and good connection with the sea, through which passed the Viking raids in England. On account of trading interests, fishing, and shipping, the State has maintained the channel by extensive protecting and regulating works, groins, and dikes. The latest measures in this respect are embodied in the Act of August, 1946, which provided for the construction of two big jetties, one on each side of the channel, and a new solid dike about 1 1/2 mi from the sea. The dike will be built later across the channel as a dam with sluices [BRUUN, 1953].

Immediately after the breach the barriers began curving inwards toward the channel, so that today the shoreline of Thyboron is situated about 1 1/4 mi farther landward than in 1791. The curving of the barriers is caused by erosion in connection with the difference in water level (up to about five feet) between the sea and the inlet prevailing during westerly gales, the result of which is that the water with suspended material is sucked into the inlet, where the solids are deposited in large shoals. At present about a million cubic yards of sand are deposited annually, whereas the annual average erosion of the barriers is 1 1/2 to 2 yd on the southern Barrier and 2 to 3 yd on the northern Barrier.

The development of the beach profiles along the Lime Inlet Barriers--Soundings along the Barriers have been carried out since 1874 in profiles about 600 yd apart. The beach profiles in general probably first obtained their maximum steepness, out to 30 to 40-ft depth, in 1927-1934. As greater fluctuations in the beach profiles along the Barriers, as far as can be seen, first occur when the profiles have developed to a certain steepness, it seems probable that a connection between the fluctuation of the beach profiles and wave conditions can be found only where the profiles are not very far from their maximum steepness, that is, between the four profiles L5-L8 on the northern Barrier and between the four profiles L31-L34 on the southern Barrier (Fig. 6). All these profiles have been relatively steep since 1909. Perhaps it will be possible to obtain a result for the whole coast of the southern Barrier, as the increase in steepness has not been very pronounced since 1909. On the northern Barrier the profiles have steepened continuously until 1934.

Definition of the mean depth and the steepness characteristic of the beach profile--The mean depth is the average depth of the water area over the length of the profile. The steepness characteristic of the beach profile is the ratio of the mean depth to the length of the profile.

In Figure 7 the mean depth equals the water area A over the length a (= A/a). The steepness characteristic (a steepness parameter) in per thousand is $1000\,A/a^2$.

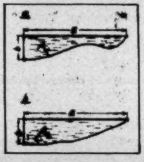

Fig. 7--Diagram showing two hypothetical profiles normal to a beach; both have the same depth b at the distance a from shore, but the lower has the greater steepness characteristic

A more practical value for the steepness of the beach profile can be obtained by multiplying the steepness characteristic by two, since the mean depth is situated in the middle of the profile.

The reason for which the terminology steepness characteristic is introduced is that the two different profiles in Figure 7 in the normal way of speaking have the same steepness = b/a, because the depth contour considered is situated the same distance from the shoreline, though the lower in reality is much steeper than the upper.

Calculations of the standard deviation of the mean depth and the steepness characteristic of the single beach profile show that both of these are so small that they can be neglected.

If the mean depth or the steepness characteristic of the single profile is taken as a representation for a coast stretch of about 600 yd situated on both sides of the particular profile, the standard deviation in determination of the average mean depth is about seven per cent for the 0 to 20-ft area, about three per cent for the 20 to 30-ft area, and about two per cent for the 0 to 30-ft area. The corresponding values for four lines (2400 yd) are about five, one, and one per cent; and for 16 lines (10,000 yd) about three, less than one, and less than one per cent.

If the steepness characteristic of the single profile is taken as a representation for a stretch of coast of about 600 yd situated on both sides of the particular profile, the standard deviation in determination of the average steepness characteristic is about six per cent for the 0 to 20-ft area, about 15 pct for the 20 to 30-ft area, and about five per cent for the 0 to 30-ft area. The corresponding values for four lines (2400 yd) are about three, ten, and three per cent; for 16 lines (10,000 yd) about two, four, and one per cent.

Comparison between the development of the beach profiles and wind conditions--From the investigations with beach profiles mentioned in Sections 2 and 3 we know that it is the strong onshore gales which cause the beach profiles to flatten out. In Figure 4, which shows results of laboratory experiments with beach profiles, the steepness characteristic at $x/L_o = 0.06$ is 50 o/oo for the storm profile a, and 75 o/oo for the swell profile c. Storms, therefore, are especially important for investigations of the fluctuations of beach profiles.

In the investigations mentioned below, meteorological observations from Vestervig, situated on the west coast not very far from the Lime Inlet Barriers, are used. Observations are made three times every 24 hours. Only wind velocities ≥6 Beaufort have any importance. Of these observations, more than 80 pct have directions between southwest and northwest; that is, that they are on the average perpendicular to the shoreline.

Table 1--Comparison between steepness and wind-action

Item	Interval								
	1909-1916	1916-1921	1921-1927	1927-1934	1934-1938	1938-1942	1942-1950	1934-1942	1934-1950
L5-L8 steepness o/oo	10.0	9.2 ↑	10.9	10.6 ↑	11.0	10.0 ↑	. . .	11.0 ↑	. . .
1.6 miles steepness o/oo	9.2 ↓	10.9	10.6 ↓	11.0	10.0 ↓	11.0	. . .	11.0 ↓	. . .
L31-L34 steepness o/oo	7.9	7.5 ↑	8.1	7.9 ↑	8.9	. . .	8.4 ↑	. . .	8.9
1.7 miles steepness o/oo	7.5 ↓	8.1	7.9 ↓	8.9	8.4 ↓	. . .	8.8	. . .	8.8 ↓
SB[a] steepness o/oo	7.6	7.5 ↑	7.5 ↑	7.8 ↑	8.9	. . .	. . .	. . .	. . .
6 miles steepness o/oo	7.5 ↓	7.5 ↓	7.8	8.9	8.2 ↓	. . .	. . .	. . .	. . .
Observation per year wind force		↑		↑		↑		↑	
6 or 7 Beaufort	66.8	36.8	41.7	39.0	49.2	53.4	88.0	51.3	69.5
8 or 9 Beaufort	14.3	8.0	11.5	4.6	9.7	9.8	17.7	9.8	13.7
10 or 11 Beaufort	2.5 ↓	0.4	1.3 ↓	0.2	0.0 ↓	0.3 ↓	0.7 ↓	0.2	0.5 ↓

[a] Southern Barrier.

Table 1 shows a comparison between the development of the steepness characteristic for the southern Barrier, L5-L8 and L31-L34, and meteorological observations. In the table is shown the number of observations per year between south over west to north with Beaufort force ≥6. Observations with force 6 or 7, 8 or 9, and 10 or 11 are taken separately. The different velocities are not weighted in the following discussion because of our lack of knowledge in detail of these problems.

The arrows pointing down in the column for steepness indicate decreasing steepness; an arrow pointing up indicates increasing steepness. These arrows are put on as follows: Consider the period 1927-1934. The average number of wind observations per year with force 6 or 7, 8 or 9, or 10 or 11 is less than the number of observations for the adjacent periods; that is, the coast must have been attacked proportionally less by storm waves in the period considered. Consequently, it can be expected that the profile has steepened.

From the table it can be seen that there is basis for the assumption that there is a connection between wind (wave) and beach profile conditions as periods with proportionally more and stronger storms coincide with periods of decreasing steepness.

As regards the conditions since 1938, it must be noted that a continuous strong-wave attack following the great decrease in steepness (for 1938) may increase the steepness until a certain degree when the beach profile has been too flat. There may also be reason to believe that material from greater depths than 30 ft has been carried to nearshore sections of the beach profile.

Examples from Denmark on the use of investigations with beach profiles in engineering practice and geographical science

Maintenance of an outlet--The manner in which littoral drift took place along the beach in the laboratory tests has already been explained. If there is a bar, waves ordinarily will break on the bar, giving rise to much suspended-load transport. After this, the waves will break again close to the shoreline, giving rise to suspended load transport in the breaker zone and bed-load transport on the beach itself. The main part of the littoral drift accordingly takes place partly on the bar and partly on the beach. If now the bar disappears, no bar drift can take place, and the littoral drift, therefore, will be concentrated more on the beach itself. That means that a jetty or a groin located in the beach profile inside the bar will now accumulate more material. Meanwhile, the groin can only collect material to a certain degree before material again drifts past the groin. If the jetty protects an outlet or a harbor entrance, perhaps "sanding up" will take place between the jetties because of the unusually strong drift. Figures 8 and 9 are charts of the outlet from Nissum Inlet on the Danish North Sea coast. The outlet is protected by two jetties. Until 1944 both of them were 500 ft long. In 1944-1947 the north jetty was extended 200 ft. Figure 8 shows the situation on June 23, 1941, where the outlet conditions were particularly bad, with depths less than three feet between the jetties (usually six to seven feet). It can be seen that there is no bar. Figure 9 shows the conditions on November 7-11, 1942. There is a bar, and at the same time the outlet conditions are very good with depths of about eight feet between the jetties. Figure 10 is a photograph taken in 1951, showing the jetties and waves breaking on the bar about 300 ft outside the outer ends of the jetties. The outlet conditions at that time again were very good. The problem of sanding up, which always takes place when the bar disappears, can be explained from the laboratory experiments.

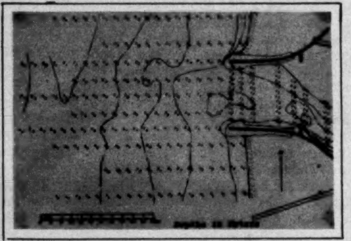

Fig. 8--Nissum Inlet in 1941; soundings in meters

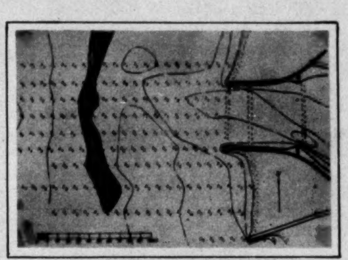

Fig. 9--Nissum Inlet in 1942; soundings in meters

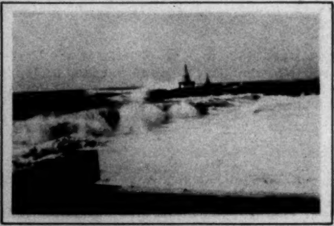

Fig. 10--Waves breaking on the bar at Nissum Inlet in 1951

What must be done to maintain good outlet conditions is to construct groins on the updrift side of the outlet. These groins would act as sandtraps and, therefore, should be comparatively high. Two 650-ft groins have been constructed north of the outlet, and two other 350-ft groins south of the outlet. At the same time the north jetty, as mentioned above, has been extended about 200 ft. If the updrift side of the groins and the north jetty, under no-bar conditions, are filled with material, a bulldozer must be used to keep removing material until such time as a bar develops again.

Construction of dikes by means of beach material--As material on the beach, situated between the winter profile and the summer profile, is eroded in the winter, it seems a good idea to bulldoze away this material and use it, for instance, for dike reinforcement on the inner side of a dike on an eroding beach. Naturally this material will be lacking in the winter profile in deeper water, but it may here be replaced not only by material eroded from the beach, but by material from the littoral drift, that is, a sand trap possibly has been produced. If material is not lacking on the down-drift side, where accretions usually take place, better equalization of material has been carried out. Even if the material is lacking in the beach profiles in deeper water, and a slight increase in erosion therefore may take place, it seems to be much better on an eroding beach to have the material on the inner side of the dike than as surplus, or migrating, material in the beach profile.

Evaluating the stability of a beach profile--The long periodic fluctuations of beach profiles along the Lime Inlet Barriers have been previously discussed. It is very important to know that these heavily eroded beaches (retrogradation of the shoreline about 8 to 12 ft per year) with maximum steepness show normal seasonal fluctuations, because that must mean that the profiles, apart from the comparatively small seasonal fluctuations, are stable. Therefore, there is no reason to expect deterioration of the area behind the dikes, when these are always kept at a certain distance from the shoreline (400 to 500 ft).

Geographic and geologic science--On the spot in the Lime Inlet indicated by cross-hatching in Figure 1, a system of very large beach ridges is found (Fig. 11). The dimensions of these ridges show that they could not have been produced by waves generated within the Lime Inlet. During the Litorina time about 3000 years ago when Denmark was submerged [JESSEN, 1920], waves from the Skager Rack penetrated into the Lime Inlet from the northwest between several islands built up of chalk and moraine, for instance, Hanstholm and Bulbjaerg (Fig. 1). By refraction in the sounds and refraction and diffraction in the Lime Inlet behind these islands, the waves changed to swells which built up beach ridges of material available on the sea bottom and produced by erosion in earlier geological periods. An evaluation of the dimension of the waves in the North Sea and the Skager Rack is difficult to carry out because of the possibility of interference between waves from north and west (crossing orthogonals).

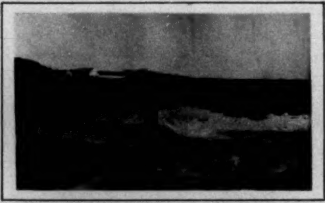

Fig. 11--Large beach ridges in the Lime Inlet

Conclusions--From the above mentioned it appears that basic research even in small scale dimensions is useful in engineering practice. It will be of interest in actual experiments under idealized conditions to investigate the relationship between steepness characteristics and steepness ratios of the waves.

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SOME OBSERVATIONS ON THE EFFECT OF PARTICLE SHAPE ON THE MOVEMENT OF COARSE SEDIMENTS

E. W. Lane and E. J. Carlson

Abstract--During a study in which information was gathered to improve the design of unlined canals in coarse granular materials, an opportunity was afforded to study the effect of particle shape on the movement of coarse sediments. This paper summarizes the various measurements and analyses that were made on samples of bed material from several canal sections in the San Luis Valley in southern Colorado. Some comparisons are made to show the resistance to movement of various shaped particles according to sphericity and Zingg type. It is pointed out that flat particles tend to become imbricated, and they resist movement more than spherical particles of equal weight. Some observations are made on the effect of dilatancy on scour and sediment movement.

Introduction--During the years 1950-52, personnel of the Bureau of Reclamation made studies to increase the information available for design of unlined canals in coarse granular materials. Several canals in such material that had straight reaches and stable beds were investigated in the San Luis Valley in southern Colorado. The canals were dug through material deposited in an alluvial cone by the Rio Grande River many years ago. The valley floor varies in slope from approximately 30 ft per mile at the apex of the cone to practically level near the middle of valley. Test sections, as shown in Figure 1, were chosen on the canals that were unusually straight and uniform

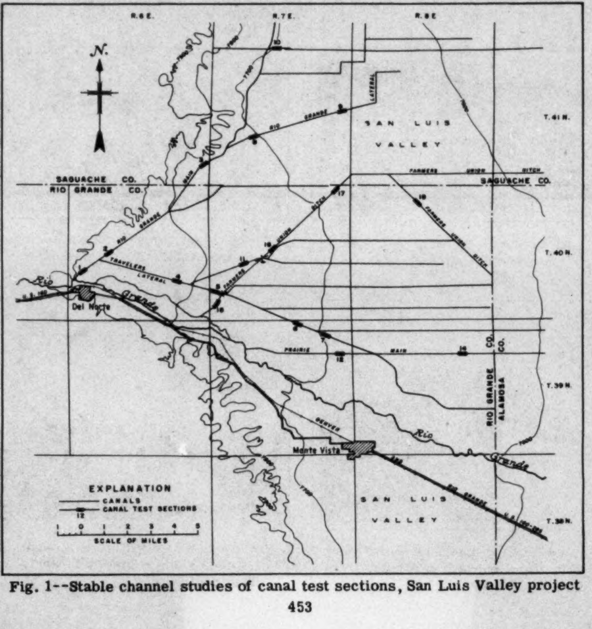
R.6E.
R.7E.
R.8E.
N.
SAN LUIS VALLEY
T.41N.
T.40N.
T.39N.
T.38N.
SAGUACHE CO.
RIO GRANDE CO.
FARMERS UNION DITCH
RIO GRANDE MAIN
LATERAL
TRAVELERS LATERAL
PRAIRIE MAIN
Rio Grande
Del Norte
Monte Vista
DENVER RIO GRANDE
RIO GRANDE CO.
ALAMOSA CO.
SAN LUIS VALLEY
EXPLANATION
CANALS
CANAL TEST SECTIONS
12
1 0 1 2 3 4 5
SCALE OF MILES

Fig. 1--Stable channel studies of canal test sections, San Luis Valley project

Table 1--Data on San Luis

Test Section	Median size bed material	1950 measurements						
		Q	Mean velocity	Slope of energy gradient	Manning's n	Mean depth	Top width	Water temperature
	inch	cfs	ft/sec			ft	ft	°F
1	3.23	944	4.80	0.00271	0.033	4.09	66	55
2	3.03	366	3.91	0.00375	0.036	2.43	52	52
4	2.99	456	4.65	0.00362	0.032	2.68	47	55
5	2.12	289	4.36	0.00371	0.030	2.25	37	57
6	1.65	101	3.57	0.00299	0.027	1.61	20.9	54
7	1.62	40.9	2.77	0.00290	0.029	1.29	14.8	57
8	1.54	11.0	1.34	0.00319	0.036	0.56	18	65
10	2.52	7.6	1.52	0.00973	0.059	0.51	10.7	56
11	1.89	124.5	2.71	0.00213	0.030	1.69	31.9	55
12	1.34	99.0	3.53	0.00240	0.024	1.61	21.5	57
14	0.79	64.7	2.56	0.00126	0.024	1.59	20.6	55
15	1.97	201	3.65	0.00194	0.025	2.20	35.1	53
16	1.93	194	3.47	0.00202	0.024	1.82	33.8	57
17	1.50	197	3.68	0.00267	0.026	1.60	37	61
18	0.83	62.5	2.21	0.00083	0.021	1.72	20	55

in section, making the sections ideal for studying the effects of particle shape on the movement of coarse sediments. Photographs on Figures 2-5 show the nature of the canal test sections.

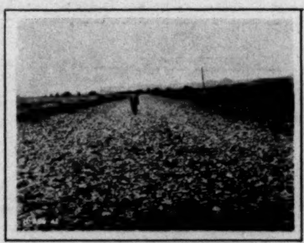

Fig. 2--Looking upstream on travelers lateral at Test Section 4

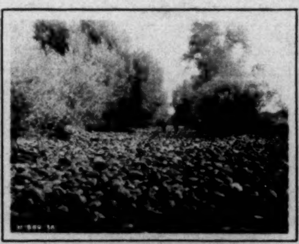

Fig. 3--Looking downstream on Rio Grande Canal at Test Section 2

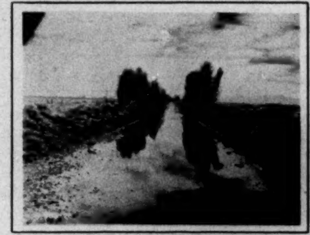

Fig. 4--Looking upstream on farmers Union Canal one mile upstream from Test Section 18

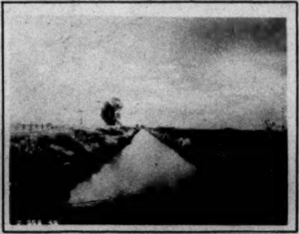

Fig. 5--Looking upstream on Prairie Canal 2-1/2 miles downstream from Test Section 12

Valley Canal Test Sections

1952 measurements							Maximum sustained discharge
Q	Mean velocity	Slope of energy gradient	Manning's n	Mean depth	Top width	Water temperature	
cfs	ft/sec			ft	ft	°F	cfs
1500	5.88	0.00280	0.031	4.87	73	47	1500
668	5.83	0.00376	0.027	2.81	55	44	729
768	6.53	0.00359	0.025	3.11	48	44	768
448.2	5.82	0.00368	0.026	2.5	40	46	448
159	4.59	0.00295	0.022	1.88	21.7	48	159
95.6	4.36	0.00290	0.022	1.73	15.9	46	96
46.0	3.00	0.00316	0.024	0.96	19.2	50	46
16.6	2.90	0.00965	0.031	0.60	11.1	52	16.6
203	3.88	0.00235	0.025	1.88	32.3	45	203
128	4.00	0.00243	0.023	1.77	21.9	52	135
110	3.29	0.00136	0.022	2.00	21.4	51	127
477	4.84	0.00199	0.026	3.05	39.4	46	500
....	....	No data taken		...	...	..	516
531	5.51	0.00274	0.024	2.60	41	51	531
235	3.80	0.00080	0.018	2.94	25	50	278

Hydraulic measurements of the water-surface slope, discharge, and cross-section areas were made, and from these measurements the Manning's roughness value n and the shear or tractive force on the bed were determined. Results of the hydraulic measurements are reported in a paper by LANE and CARLSON [1953]. So the reader will have some idea regarding the hydraulic conditions, Table 1 is presented which gives pertinent data on the San Luis Valley test sections. Tables 2 and 3 give, respectively, the mechanical analyses of the bed materials and of the natural materials in the banks for all test sections.

Table 2--San Luis Valley Canal test sections, bed materials, mechanical analysis

Canal Test	Per cent passing U. S. Standard sieve size by weight				
Section	3 inch	1-1/2 inch	3/4 inch	3/8 inch	No. 4
1	25.8	8.5	0.3	0	....
1	29.2	4.0	0.3	0	....
2	45.9	7.0	0	....	....
4	45.2	7.6	0.4	0	....
5	84.0	15.4	0.5	0	....
6	99.4	33.2	7.9	2.4	0
7	100	31.4	2.1	0	....
8	87.6	47.7	11.2	1.8	0
9	99.4	42.7	4.0	0.5	0
10	61.6	17.1	1.3	0	....
11	93.4	20.9	2.5	0.2	0
12	100	61.0	9.0	1.0	0
14	100	100	38.5	3.5	0
15	83.9	23.2	1.1	0	....
16	80.4	30.5	2.9	0.6	0
17	100.0	47.2	8.9	0.6	0
18	100	98.0	37.4	5.0	0

Table 3--San Luis Valley Canal Test Sections, natural material in banks, mechanical analysis

Canal Test Section	Per cent passing U. S. Standard sieve size by weight										
	3 inch	1-1/2 inch	3/4 inch	3/8 inch	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200
1	74.0	63.5	43.8	30.7	24.5	22.5	19.7	13.5	8.3	5.3	3.6
2	85.1	61.7	46.3	37.8	32.4	31.0	27.9	20.9	15.5	11.3	8.3
4	92.9	82.3	67.2	57.1	49.5	44.0	37.6	28.3	19.3	13.0	10.3
5	92.9	75.8	62.6	52.5	45.6	44.0	41.4	35.8	22.3	9.3	4.8
6	100	77.3	61.3	46.9	36.6	31.5	22.0	11.8	7.8	4.7	3.0
7	100	95.4	69.1	52.1	38.1	32.5	26.6	20.4	14.1	8.0	5.4
8	100	91.8	80.0	70.6	59.3	47.9	29.3	14.2	6.4	2.8	1.9
9	100	96.9	89.4	82.0	70.8	58.3	49.8	40.6	31.5	25.4	20.9
10	100	69.1	51.0	40.7	33.0	31.0	27.5	21.8	14.5	9.2	6.3
11	100	88.5	59.5	49.5	42.5	37.2	31.2	19.8	12.0	7.7	5.3
12	100	90.8	77.6	59.7	46.4	41.0	31.8	19.8	9.7	4.0	2.4
14	. . .	100	94.7	76.6	63.3	55.4	51.2	46.1	35.8	25.0	20.2
15	93.9	76.5	59.2	52.6	49.0	48.3	47.3	41.8	30.0	24.0	20.1
16	100	89.8	74.5	56.6	43.9	38.6	34.2	27.3	15.6	7.0	4.4
17	100	82.0	68.6	57.2	50.0	46.4	41.5	31.4	20.3	13.2	11.9
18	100	99.0	87.0	70.5	61.7	58.5	54.1	43.5	30.4	22.0	15.8

Measurements of particle shape--Detailed measurements of particle shape consisting of measurements of the three principal axes of the particles and a determination of their weight were made on the samples from the beds of ten test sections.

The measurement of the three axes were made with instruments designed and built in the Hydraulic Laboratory. Measurements of larger particles were made with the instrument shown in Figure 6. The major diameter is read directly on the scale of the large sliding face, and the intermediate and minor axes are read directly from the movable support and measuring stick. In Figure 6a the minor axis of the rock shown is 10.2 cm, and in Figure 6b the intermediate axis is 13.2 cm. The axes of the smaller rocks were measured with a smaller instrument developed by Appel [see KRUMBEIN, 1938, p. 145] in which the rock was turned to measure each axis. From these data, the sphericity and ZINGG [1935] type were determined. Visual determinations of the roundness were also made. The sphericity measure used was KRUMBEIN's [1941] approximation to WADELL's [1932, 1933, 1935] definition of sphericity as the cube root of the ratio of the volume of the particle to the volume of the circumscribing sphere. This is equal to cb/a^2 where a, b, and c are, respectively, the major, intermediate, and minor axes, the axes being measured at

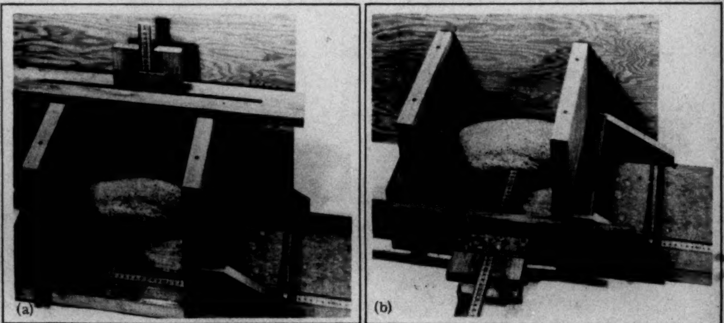

Fig. 6--Instrument for measuring three axes of individual particles: (a) position for measuring major and minor axes; (b) position for measuring intermediate axis

Table 4--Zingg's classification of particle shape

Class	Shape	b/a	c/b
I	Disks	> 2/3	< 2/3
II	Spherical	> 2/3	> 2/3
III	Blades	< 2/3	< 2/3
IV	Rodlike	< 2/3	> 2/3

right angles to each other. The Zingg type is found from the relation of the axes as shown in Table 4. The roundness was determined by visual comparison of the particle with a chart prepared by KRUMBEIN [1941] based on Wadell's method of specifying roundness. This is the ratio of the average radius of curvature of the edges and corners of the image of the pebble to the radius of the inscribed circle.

On Table 5 is shown the shape composition of the bed material of ten of the canal sections in terms of the percentage of the number of particles in each class. The shape in terms of the Zingg classification, sphericity, and roundness is given; and average values for each class are also given. The classification of sphericity, which is based on actual measurements of the three axes, shows that the distribution among the classes for all test sections follows very nearly the same pattern. The deviation of the distribution of any individual test section from the average of all sections is very small as shown on Table 5.

Table 5--Classification showing per cent of total number of particles in each class

Test Section	Zingg class				Sphericity class						Roundness class							
	I	II	III	IV	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0 8	0.8-0.9	0.9-1.0	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1	44	32	6	18	1	10	31	40	17	1	...	1	6	21	31	25	12	4
2	47	29	6	18	1	10	35	40	13	1	...	1	5	16	37	26	11	4
3	33	36	14	17	3	12	31	37	16	1	...	2	14	25	33	19	6	1
4	46	27	11	16	1	13	30	38	16	2	...	2	4	15	39	22	15	3
8	34	37	10	19	2	12	33	32	18	3	1	5	16	23	28	17	7	3
9	37	39	9	15	2	8	29	37	20	4	...	5	14	16	33	20	9	3
10	39	32	15	14	3	17	33	27	17	3	1	3	13	36	31	11	4	1
11	34	41	10	15	3	9	29	37	16	6	...	7	10	33	34	13	12	1
14	27	45	12	16	2	11	24	39	23	1	2	6	10	33	34	12	3	...
16	39	34	9	18	2	11	30	39	16	2	1	1	4	21	24	31	13	5
Average all sections	38	35	10	17	2	11	31	37	17	2	...	3	10	24	32	20	9	2

Plotting the sphericity distribution of each of the test sections on arithmetic probability paper where the sphericity class is the arithmetic scale and the per cent smaller than the given class is plotted along the probability scale, the distributions from the individual test sections are very close together and very nearly to straight lines. The probability plot indicates the distribution of the sphericity classes, according to number of particles in each class, and follows very closely to the normal error or probability distribution. The median sphericity of particles from all test sections was 0.70, and the standard deviation from the median value was 0.103.

A probability plot for the roundness distribution was made in the same way as described for the sphericity distribution. In classifying individual sediment particles according to the roundness it was necessary to determine their class by visual comparison of the particle with diagrams. It was possible, therefore, to have some human error in the classification. It is believed the human error may account for the greater deviation in the roundness classification. The median point of the average roundness classification is at 0.59. The standard deviation from the median value is 0.137. The plots of the roundness are very close to straight lines on the probability paper, indicating these distributions follow very closely to the normal error or probability distribution. The classification according to Zingg type is not applicable to probability plotting.

A petrographic examination of about 350 cobbles from the surface of the canal bed near the upper end of the canal system was made to determine the nature of the rocks involved. This examination showed that the principal types of rock were andesite 71 pct, rhyolite 9 pct, syenite 6 pct, and miscellaneous igneous 14 pct. The average specific gravity of all rocks measured from three test sections was 2.56.

Studies of imbrication--During the course of the studies on the San Luis Valley canals, it was noticed that the material on most of the canal beds was arranged in a definite pattern. The first indication of this was when it was observed that the same canal bed had a different appearance to one standing on the bed and looking upstream from the appearance when looking downstream. When looking upstream the cobbles appeared to be smaller than when looking downstream. A comparison of Figures 7 and 8 taken looking in opposite directions from the same point in the bed of Test Section 1 shows the difference in appearance. A closer examination of the bed material showed it was not an optical illusion but was due to the fact that large numbers of the flatter cobbles were arranged with their flatter faces sloping upward in a downstream direction or, in other words, that they were arranged like shingles on a roof. In looking upstream one sees the downstream edges of the flat cobbles, and in looking downstream one sees the flat faces which are larger than the downstream edges.

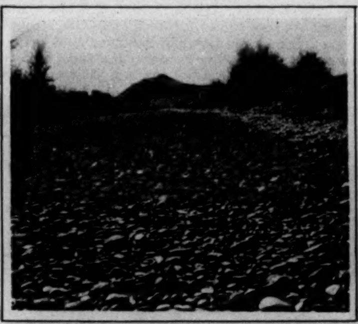

Fig. 7--Looking upstream at Test Section 1

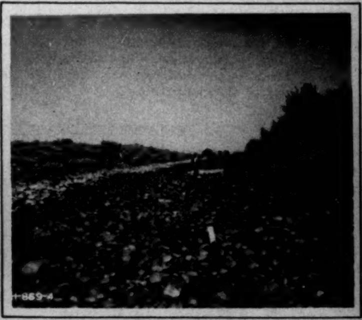

Fig. 8--Looking downstream at Test Section 1

The shingling or imbricated arrangement of the cobbles is believed to be the result of the forces acting on a flat cobble arranged in this position. When a flat-shaped cobble is placed in a current with its flat face sloping upward in the direction of flow, there is a force as shown in Figure 9 acting downward on the cobble due to its deflection of the direction of the current. On the downstream side there is a tendency for a lowered pressure to form due to the curvature of the stream lines which causes an additional force B acting downward. If this cobble comes to rest on other cobbles in this position, these forces tend to hold it down and keep it in place. Hence this shaped cobble tends to rest in this position on the bed. If it rested sloping down in a downstream direction, the direction of the forces would be reversed and there would be an upward force on the lower side which would tend to overturn the cobble. In the former position the cobble is very stable because the greater the velocity the greater are the holding-down forces. This action is similar to that observed when a stream of water from a fire hose is played on a shingle roof.

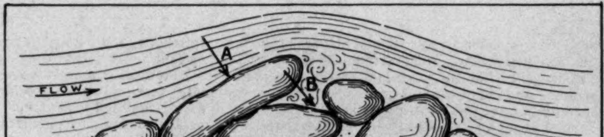

Fig. 9--Force holding flat particle in place on canal bottom

When the stream is directed down the slope the shingles are not disturbed, but when it is directed up the slope the shingles are torn off.

It may be said, therefore, that when flat particles are in the imbricated position they are generally stable and stay in place; and when they are not in this position they tend to be unstable and move. This results in a strong tendency of the flat particles to assume the imbricated position and, hence, produce the generally imbricated pattern observed in the San Luis Valley canals.

It was also noticed that the elongated cobbles were usually arranged with their longest dimension at right angles to the direction of flows as shown in Figure 10. The point on the scale indicates the direction of flow. Although in Figure 10 the orientation is more pronounced than average conditions, even under average conditions the orientation is sufficiently pronounced to permit an accurate determination of the direction of the current from an examination of a photograph of the bed material.

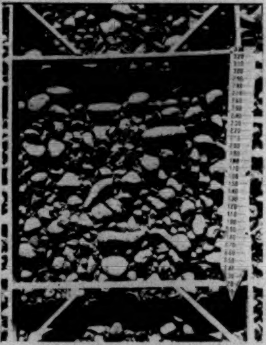

Fig. 10--Long axis of particles oriented at right angles to direction of flow, Test Section 3

It is believed that the reason for the elongated cobbles arranging themselves across the direction of flow is that they have rolled downstream by the current, and when a cobble rolls it naturally does so with its long axis normal to the force causing motion. When it comes to rest, it is in this position.

It was also noticed that, except for some of the top cobbles which rested only on other cobbles, most of the larger cobbles which formed the bed rested on sand which fit closely around the lower portion of the cobble. When these cobbles were raised from the bed, an impression or cast of the shape of the cobble remained in the sand.

Effect of particle shape on movement--In the foregoing paragraphs it has been shown that there was a tendency for the flat particles to be held against the bottom in an imbricated manner by the flowing water, and the elongated particles to arrange themselves with their longest axis at right angles to the flow. This indicates that there are two types of action involved in the composition of the bed of a canal in coarse, noncohesive material when subject to high tractive forces.

In order to obtain quantitative data on the effect of particle shape on their susceptibility to movement by flowing water under the San Luis Valley conditions, an analysis was made of the relative size of particles of different shape which comprised the top layer of Test Section 1 of the San Luis Valley canals. The analysis was made on the hypothesis that the material remaining on the bed of these canals would show how susceptible various shapes were to movement. For example, if it could be shown that the flat particles were of smaller weight than the spherical particles, it would indicate that flat particles were less susceptible to movement than spherical particles of equal weight. Figures 11 and 12 show the results of an analysis made on this hypothesis. In Figure 11 a comparison is made between particles of disk shape according to the Zingg classification with particles in the sphere class. The other two Zingg classifications were not included in the study as the numbers of particles in these classes in the samples available were insufficient to give accurate results. One curve of Figure 11 gives the proportion of the total weight of disk-shaped particles in the sample that is composed of particles of smaller weight than the values shown on the left-hand scale. The other curve gives similar data for spherical particles. These curves are similar to mechanical analysis curves but use particle weight instead of diameter. For example, the curves show that 50 pct of the total weight of the disk-shaped particles was made up of particles having weights of less than 1300 grams, and 50 pct of the weight of spherical particles was made up of particles having a weight of less than 3500 grams. Assuming that the particles in the same percentage range are of equal susceptibility to movement, for example, that the disks in the 50 to 60 pct ranges are of the same susceptibility to movement as the spheres in the same percentage range, the comparison shows that on the average the disks are of the same susceptibility to movement as spheres with weights 2.5 times as large.

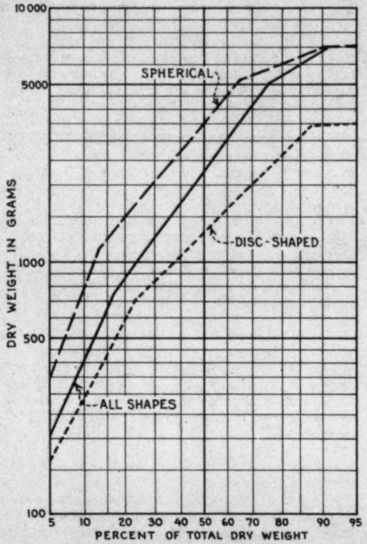

Fig. 11--Comparison of spherical with disc-shaped particles, San Luis Valley Test Section 1

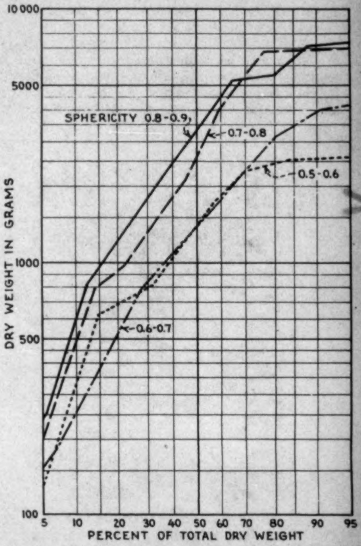

Fig. 12--Comparison of sphericity of all particles measured, San Luis Valley Test Section 1

A similar analysis was made of particles with different sphericity values. The results of this comparison are shown in Table 6 which shows, for example, that the particles in the 0.8-0.9 sphericity range weigh 1.67/0.63 = 2.65 times as much as the particles in the 0.5-0.6 sphericity range which have the same susceptibility to movement. It also shows that there is little difference in susceptibility to movement between particles in the 0.5-0.6 and 0.6-0.7 classes, and also between the 0.7-0.8 and 0.8-0.9 classes, but a much greater difference between those in the 0.6-0.7 and 0.7-0.8 classes.

Table 6--Effect of shape on relative susceptibility to movement as contact load

Sphericity range	Relative weights of particles of equal susceptibility to motion
0.5 - 0.6	0.63
0.6 - 0.7	0.67
0.7 - 0.8	1.25
0.8 - 0.9	1.67

It is not clear to what extent the composition of the material in the top layer of the canal beds was the result of deposition from the flowing water that formed the valley floor through which the canals were constructed, and to what extent it was influenced by the water flowing in the canals. It is probable that both influences were involved, but, in any event, the particles of all shapes were influenced by the same flows. It is probable that more exact values of relative susceptibility to movement would be obtained by using particles which had been subject to only one type of water action. However, no shape analyses were made of particles from the original material through which the canals were constructed, and, therefore, such an analysis was not possible in this study.

It is hoped that pointing out the method of analysis used in this case will lead others to make further studies in this field.

It is interesting to compare the results of these observations of movement of coarse material moving as contact load with what is known of the movement of material in suspension. The movement of material in suspension is a combination of two actions, (1) the lifting of the particle from the stream bed, and (2) the settling of the particle back down to the stream bed. In the latter of these two, the action is similar to the settling of the particle in quiet water. It is well known that the settling rate of disk-shaped particles is less than that of spherical particles of the same weight. During the second action a disk-shaped particle, since it settles more slowly, would be transported a greater distance before it settles to the bottom than would a spherical one, and during this phase disk-shaped particles are, therefore, more readily transported than spherical particles. It will be seen that this is the reverse of the condition of transportation as contact load where disk-shaped particles are less readily transported than spherical particles. As a result, the laws governing transportation by contact load must be quite different from those governing suspended load.

The picking-up action of sediment going into suspension is no doubt very complex. To a certain extent, it is related to the lift of the water passing over the particle. It is not unreasonable to suppose, however, that the start of the motion of the particle as it goes into suspension may have, at least in part, the same sort of motion as that of the particle moving in contact load. If this is the case, in the first phase of suspended sediment transportation mentioned above, the shape of the particle may influence the sediment transportation in a very different way from its influence in the second phase, and the influence of shape on the settlement rate of a particle would not be a complete index of its influence on the susceptibility of a particle to transportation in suspension.

Possible effect of dilatancy on scour and sediment movement--The presence of the sand in close contact with the bottom of the cobbles covering a large part of the canal beds is believed to have an effect on the ability of the bed to resist scour when acted upon by turbulent flow. For one of these bedded cobbles to be lifted from its bed, it is necessary for water to pass into the space between the cobble and the bed as the cobble is lifted up. If the water does not enter this space fast enough when the particle is lifted, a partial vacuum is formed which tends to hold the cobble down. The water can enter this space by flowing through the sand beneath the cobble or by entering along the contact of the cobble with the sand. For water to enter along this contact, a slight movement must already have taken place. If a constant force is applied to the cobble slightly in excess of that which would be required to move it without this vacuum effect and is permitted to act long enough, sufficient water can flow through the sand to fill the space below the cobble and allow it to break contact with the sand. This will allow the water to flow in along the contact, and greater movement of the cobble will take place without forming a partial vacuum. However, if the force is not applied long enough for the water to move in, no movement or only a very slight movement will take place before the force ceases and the cobble sinks back into its original position. The susceptibility of a particle to movement would thus depend on the length of time the forces act on it, as well as the magnitude of these forces. A certain force produced for a short time by small-scale turbulence in the flowing water might not be sufficient to move the cobble away from its position on the bed, while a force of the same magnitude applied over a long time by large-scale turbulence might cause the movement. In other words, the susceptibility of the canal bottom to scour would be a function of the magnitude of the turbulent eddies.

The necessity of the water to enter the space under the cobble when it is moved is a special case of the dilatancy effect first suggested by REYNOLDS [1885] for whom the Reynolds' number in fluid mechanics is named. Reynolds noted the hardness of the wet as compared with the dry sand on a sea beach and described in considerable detail this action and the causes of it. He was the first to propose the term dilatancy previously mentioned.

Reynolds then went on to develop a hypothesis for the constitution of matter. This hypothesis, unlike his Reynolds' number in fluid mechanics, has not been accepted by physicists, but his explanation of the dilatancy phenomena which he observed has been widely applied in soil mechanics and to some extent in geology [MEAD, 1925]. It is interesting to speculate as to whether this dilatancy effect may also be a factor in the picking-up action of even such small sediment particles as are carried in suspension and, therefore, be a factor in suspended sediment transportation.

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ON THE HYDRAULIC CONDUCTIVITY OF UNSATURATED SOILS

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Abstract--Unsaturated steady flow of mixtures of a liquid and a gas through sands and similar porous media at low Reynolds numbers obeys Darcy's law. The relative liquid permeability K is not constant, but a universal function of the degree of liquid saturation. An approximate theory gives its form, which is a cubic parabola. A similar expression is found for the gas permeability. Numerous experiments by Wyckoff and Botset confirm the theory. This is in agreement with Gardner's hypothesis that K is a function of the concentration in water, and indirectly with Richards' hypothesis that it is a function of the capillary potential. The degree of liquid saturation seems to be a more useful unit of liquid percentage than any other.

Introduction--The horizontal steady flow of viscous incompressible and chemically inactive fluids through saturated homogeneous isotropic and geometrically stable porous media, in the absence of compressible free gases (air, vapor bubbles), at low Reynolds numbers and constant temperature, obeys the Darcy law [IRMAY, 1947]

$$q = k/\gamma \cdot \nabla p = K/\mu \cdot \nabla p \quad \dots\dots\dots\dots (1)$$

where q = specific discharge (discharge per unit area, dimensions LT^{-1}); γ = unit weight of the fluid; μ = its dynamic viscosity; and $\nabla p = \Delta p/L$ = pressure gradient (absolute value). The coefficient k (dimensions LT^{-1}), called hydraulic conductivity [RICHARDS, 1952], is a measure of the permeability of the soil to the given fluid. The coefficient K (dimensions L^2), called specific or intrinsic permeability [MUSKAT, 1937], is a measure of the permeability of the soil to any fluid. The formula may be extended to non-isotropic media [IRMAY, 1951b], to non-homogeneous media [IRMAY, 1953; BOUSSINESQ, 1904], to geometrically unstable media [FLORIN, 1948; JACOB, 1950], to unsteady flow [IRMAY, 1951a], and to compressible fluids [MUSKAT, 1937], assuming always complete saturation of the soil with water or any other one fluid.

Degree of saturation and specific permeabilities--RICHARDS [1931] has extended the Darcy law to unsaturated flow, when part of the voids contains air in form of bubbles or even in a continuous phase. He assumes K to be a function of the capillary potential. IRMAY [1951c] studied the effect of air bubbles in the hydrostatic case. GARDNER [1946] assumes K to be an unknown function of the moisture content alone. WYCKOFF and BOTSET [1936] investigated the flow of mixtures of liquid (water) and gas (carbon dioxide) in various proportions through unconsolidated sands of widely different permeabilities. They found that the liquid specific permeability K_L and the gas specific permeability K_G depend on the degree of liquid saturation s, defined by

$$s = c/n \quad \dots\dots\dots\dots (2)$$

where c = partial volume of water in a unit volume of soil (the so-called volume concentration in water); n = porosity, or volume of voids in a unit volume of soil.

If K'_L is the value of K_L for complete saturation (s = 1) and K'_G is the value of K_G when no liquid water moves, we may define the dimensionless liquid and gas relative specific permeabilities

$$x_L = K_L/K'_L \qquad x_G = K_G/K'_G \quad \dots\dots\dots\dots (3)$$

Wyckoff and Botset plotted the experimental values of x_L and x_G versus s, and found that all the points lie approximately on one of two curves, regardless of the grain size of the sand or its heterogeneity, even over a wide range of liquid viscosities (Fig. 1). We see that x_L is practically negligible ($x_L = 0$) up to a threshold degree of saturation ($s_o = 0.10$ to 0.20), then rises steeply to its maximum value 1 at complete saturation (s = 1). Similarly, $x_G = 1$ up to a remaining degree of saturation ($s_1 = 0.10$ to 0.20), then decreases rapidly to zero at complete saturation. The x_L and x_G curves intersect at $s' = 0.55$ to 0.60; and are almost symmetrical with respect to s'.

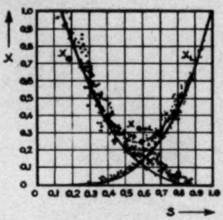

Fig. 1--Relationship of x_L and x_G to s

The x_L curve starts at $s = s_0$ only, probably due to some liquid being retained in the sharp angles between the sand grains. This always stagnant or dead water (which is so for obvious hydrodynamic reasons) might even be replaced by a filler of solid or incompressible material without altering the flow.

The x_G curve starts at $s = s_1$, because some liquid is always left in the sharp angles between grains. The removal of this 10 to 20 pct of the liquid from the sand involves practically an evaporation process, the flow comprising an essentially wet gas.

Development of the Darcy law from the Poiseuille formula--Wyckoff and Botset were unable to explain the mechanism of this remarkable regularity, yet the results agree with both Richards' and Gardner's hypotheses. What is the physical reason for this? Let us compare the simple case of the Darcy law for horizontal saturated flow with its ancestor, the Poiseuille formula for steady viscous flow in capillary tubes of length L and diameter D [IRMAY, 1947; 1951a, Ap. 2 and 3]. This formula gives the mean velocity u under a pressure gradient $\nabla p = \Delta p/L$

$$u = (D^2/32\,\mu)\ \nabla p = (R^2/2\,\mu)\ \nabla p \qquad (4)$$

R is the mean or hydraulic radius, defined as the ratio between the wetted area A (proportional to the driving force) and the wetted perimeter P (proportional to the friction or drag resistance)

$$R = A/P \qquad (5)$$

In a circular tube $4R = D$. Dimensional reasons lead us to assume the validity of (4) for tubes of any shape and even for porous media. The numerical coefficient may change a little and R may have to be redefined as the ratio of the volume of liquid (driving force) to the total area of the sand grains contained in a unit volume of soil (drag resistance), or the so-called specific surface M.

The volume of liquid in a saturated soil is evidently n. The total area M of the soil grains may be computed if they are approximately spherical and their texture is known to consist of N_1, N_2, . . . grains of diameter d_1 , d_2, . . . and volume (or weight) percentage α_1, α_2, . . . respectively in a unit volume of grain material

$$M = \Sigma N_i\ \pi d_i^2 = 6\,\Sigma\ (\alpha_i/d_i) \qquad (6)$$

As the grains occupy the volume (1 - n) and the liquid the volume n

$$R = n/(1 - n)\,M \qquad (7)$$

n represents the driving force and (1 - n) M the viscous drag resistance. Introducing the effective diameter $\bar{d}$

$$\bar{d} = 6/M = 1/\Sigma\,(\alpha_i/d_i) \qquad (8)$$

$$R = \bar{d}n/6\ (1 - n) \qquad (9)$$

Or the specific discharge q is smaller than the mean velocity u

$$q = nu = n\,[4\bar{d}n/6\ (1 - n)]^2/32\,\mu\ \cdot\ \nabla p \qquad (10)$$

and

$$q = K_L'/\mu\cdot\nabla p \qquad K_L' = (\bar{d}^2/72)\ [n^3/(1 - n)^2] \qquad (11)$$

This is essentially the Darcy law. The expression of K_L' has been confirmed experimentally [SULLIVAN and HERTEL, 1942; ROSE, 1943]. (Rose's experiments confirm the second equation of (11), though he does not state this explicitly in his interesting thesis.)

If we remember that part of the water in the voids is stagnant in the sharp angles between the sand grains, (7) and (10) should be replaced by

$$R = n(1 - s_o)/(1 - n)M \qquad q = n(1 - s_o)\,u$$

s_o being that part of the voids which is filled with dead water. Hence

$$K'_L = C\bar{d}^2\,(1 - s_o)^3\,n^3/(1 - n)^2 \quad \ldots\ldots\ldots\ldots \quad (12)$$

C is a numerical constant of the order 0.01, depending on the shape of grains and the soil structure.

Theoretical formulas of specific permeabilities--When the soil is not saturated, a fraction of the volume $c = ns$ is filled with water and another fraction $n - c = n(1 - s)$ is filled with gas. Let us consider the flow of water first. The driving force is proportional to the water volume $c = ns$, or rather to the effectively mobile volume $n(s - s_o)$. The viscous resistance due to the drag on soil grains remains unchanged, so

$$R_L = (s - s_o)\,n/(1 - n)M \qquad q_L = n(s - s_o)\,u$$

Hence

$$K_L = C\bar{d}^2\,(s - s_o)^3\,n^3/(1 - n)^2 \quad \ldots\ldots\ldots\ldots \quad (13)$$

At complete saturation ($s = 1$)

$$K'_L = C\bar{d}^2\,(1 - s_o)^3\,n^3/(1 - n)^2 \quad \ldots\ldots\ldots\ldots \quad (13')$$

and the relative specific permeability of the liquid

$$x_L = K_L/K'_L = (s - s_o)^3/(1 - s_o)^3 \quad \ldots\ldots\ldots\ldots \quad (14)$$

A similar reasoning for the gas phase gives

$$R_G = n(1 - s)/(1 - n)M \qquad q_G = n(1 - s)\,u$$

$$K_G = C\bar{d}^2\,(1 - s)^3\,n^3/(1 - n)^2 \quad \ldots\ldots\ldots\ldots \quad (15)$$

When there is no mobile water (remaining degree of saturation $s = s_1$)

$$K'_G = C\bar{d}^2\,(1 - s_1)^3\,n^3/(1 - n)^2 \quad \ldots\ldots\ldots\ldots \quad (15')$$

and the relative specific permeability of the gas phase is

$$x_G = K_G/K'_G = (1 - s)^3/(1 - s_1)^3 \quad \ldots\ldots\ldots\ldots \quad (16)$$

The curves x_L and x_G are shown in full lines for $s_1 = 0.10$ and $s_o = 0.20$. We see that the agreement is excellent, especially in the liquid phase. The two curves intersect at

$$s' = 0.5\,(1 - s_o s_1)/[1 - 0.5\,(s_o + s_1)] = 0.575$$

where

$$x_G = x_L = [(1 - s_o)/(2 - s_o - s_1)]^3 = 0.125 \text{ to } 0.150$$

The agreement is very good again.

The total effective relative specific permeability is proportional to the volume flow of the liquid-gas mixture

$$x = x_L + x_G = (s - s_o)^3/(1 - s_o)^3 + (1 - s)^3/(1 - s_1)^3 \quad \ldots\ldots\ldots\ldots \quad (17)$$

It is represented by the broken line on Figure 1 and has a minimum $x = 0.2$ to 0.3 for $s = s_m = 0.55$ to 0.60, which is in fair agreement with Wyckoff and Botset's results.

Table 1 gives the values of the relative specific permeabilities x_L and x_G for various degrees of saturation.

Table 1--Relative specific permeabilities x_L and x_G for various degrees of saturation

Saturation degree s	Relative specific liquid permeability, x_L			Relative specific gas permeability, x_G		
	s_o			s_1		
	0.10	0.15	0.20	0.10	0.15	0.20
0.10	0.000	....	....	1.000	....	....
0.15	0.000	0.000	....	0.843	1.000	....
0.20	0.001	0.000	0.000	0.702	0.835	1.000
0.25	0.005	0.002	0.000	0.580	0.688	0.825
0.30	0.011	0.005	0.002	0.470	0.558	0.670
0.35	0.022	0.013	0.007	0.378	0.448	0.537
0.40	0.037	0.026	0.016	0.296	0.352	0.422
0.45	0.059	0.044	0.031	0.228	0.270	0.324
0.50	0.088	0.070	0.053	0.171	0.204	0.244
0.55	0.125	0.104	0.084	0.125	0.148	0.178
0.60	0.171	0.148	0.125	0.088	0.104	0.125
0.65	0.228	0.204	0.178	0.059	0.070	0.084
0.70	0.296	0.270	0.244	0.037	0.044	0.053
0.75	0.378	0.352	0.324	0.022	0.026	0.031
0.80	0.470	0.448	0.422	0.011	0.013	0.016
0.85	0.580	0.558	0.537	0.005	0.005	0.007
0.90	0.702	0.688	0.670	0.001	0.002	0.002
0.95	0.843	0.835	0.825	0.000	0.000	0.000
1.00	1.000	1.000	1.000	0.000	0.000	0.000

Conclusions--The following conclusions are drawn:

(a) In unsaturated flow we may safely assume for sandy soils (probably others as well) that the relative liquid or gas permeabilities are universal functions of the degree of liquid saturation. There may be some deviations due to the slight variability of the threshold and remaining degrees of saturation (s_o, s_1). This confirms Gardner's hypothesis that K is a function of the concentration in water $c = ns$, and indirectly Richards' hypothesis that K is a function of the capillary potential, which depends on c.

(b) The universal law suggests the usefulness of expressing the soil moisture, not in moisture content or even water concentration c, but in the degree of saturation $s = c/n$. It seems, for example, that most soil tension versus moisture curves would thus be brought very close together.

(c) The specific permeability to the liquid probably has the form (13), hence

$$K_L = C\bar{d}^2 (s - s_o)^3 n^3/(1 - n)^2 = C\bar{d}^2 (c - c_o)^3/(1 - n)^2 \qquad c_o = ns_o \quad \ldots\ldots (18)$$

(d) We see from (13) and (13') that for a given soil the specific permeability K_L in unsaturated flow is proportional to that K'_L in saturated flow. So for a given degree of saturation, the permeabilities of different soils increase with the effective diameter $\bar{d}$ and porosity n. The same applies to K_G and K'_G of the gas phase.

(e) The ratio of volume flows of gas and liquid is given by (1) and (13) to (16)

$$q_G/q_L = (x_G/x_L)\,(\mu_L/\mu_G) = (1 - s)^3/(s - s_o)^3\,(1 - s_o)^3/(1 - s_1)^3\,\mu_L/\mu_G \quad \ldots\ldots (19)$$

The form of this curve agrees fairly well with Wyckoff and Botset's results.

(f) Wyckoff and Botset found for the higher degrees of saturation that a steady state of flow is obtained only up to a certain equilibrium saturation s_E, to which corresponds an equilibrium permeability K_E, or relative equilibrium permeability $x_E = K_E/K'_L$. At that saturation the steady flow of gas is null. s_E varies between 0.75 to 1.0, and x_E between 0.3 to 0.9, according to the soil. They found that for a given liquid and gas, K_E depends on K'_L alone, independently of the soil texture and porosity. K_E is approximately proportional to $(K'_L)^{0.8}$. They state "At these low gas/liquid ratios, gas gradually accumulates in the pores until the pressure gradient has built up sufficiently to flush some of the bubbles out of the pores, a steady state condition being obtained in which the bubbles are flushed out as rapidly as they are formed . . . . The minute quantity of gas dissolved in the tap water was sufficient to produce the equilibrium permeability."

Or we saw in (d) that K_E is proportional to K_L'. The slight variation of exponent (Wyckoff and Botset's 0.8 to my 1.0) is due to s_E varying slightly from soil to soil. In soils of low permeability the pores are small, hence the tiny gas bubbles adsorbed at the surface of the soil grains cannot grow much. In soils of high permeability the pores are big, and the bubbles may grow considerably. By similitude considerations the bubbles in the impervious soils are relatively to the pore size larger than those in permeable soils, hence they are flushed more readily and their s_E is nearer unity. This is a qualitative explanation, pending further theoretical research.

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RIVER DEPLETION RESULTING FROM PUMPING A WELL NEAR A RIVER

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Abstract--A well adjacent to a river will take a portion of its supply from the river. A theoretical formula is developed which permits the draft on the river to be computed in terms of the distance of the well from the river, the properties of the aquifer, and time. The formula applies where the river can be considered to flow in a straight course which extends for a considerable distance both upstream and downstream from the well location.

When pumping of a well near a river begins, water is drawn, at first, from the water table in the immediate neighborhood of the well. As the zone of influence widens, however, it begins to draw a part of its flow from the river and, ultimately, the river supplies the entire flow. It is the purpose of this analysis to develop a formula for estimating the amount of flow drawn from the river at any time after pumping begins.

Notation:

D	saturated thickness of the water-bearing stratum or aquifer, feet
K	permeability, ft/sec
Q	flow of the well ft^3/sec
q_1	flow crossing a straight line at a distance x_1 feet from the well if no river is present, ft^3/sec
q	the flow taken from a river at a distance x_1 feet from the well, ft^3/sec
r	a radius measured from the center of the well, feet
s	draw-down at the radius r at the time t, feet
t	time, from beginning of pumping, seconds
V	volume of water yielded by a horizontal square foot of the aquifer if the pressure is dropped one foot, dimensionless
x and y	rectangular coordinates measured from the center of the well, feet
x_1	the distance of a well from a river, measured along a normal to the direction of flow. The river is assumed to extend indefinitely upstream and downstream from the well, feet
$\alpha = KD/V$	
λ	a time variable running between zero and t, seconds

The differential draw-down ds at the time t due to removal of the quantity of water $Qd\lambda$ at the time λ is [CARSLAW, 1921]

$$ds = [Q/4\pi KD(t-\lambda)]\, e^{-r^2/4\alpha(t-\lambda)}\, d\lambda \quad \ldots\ldots\ldots\ldots (1)$$

This expression satisfies the continuity condition

$$\partial s/\partial t = \alpha[(\partial^2 s/\partial r^2) + (1/r)(\partial s/\partial r)] \quad \ldots\ldots\ldots\ldots (2)$$

and the condition that the draw-down is zero everywhere when $(t-\lambda) = 0$. Let

$$u = r/\sqrt{4\alpha(t-\lambda)} \quad \ldots\ldots\ldots\ldots (3)$$

Then, by substitution and integration

$$s = (Q/2\pi KD)\int_{r/\sqrt{4\alpha t}}^{\infty} (e^{-u^2}/u)\, du \quad \ldots\ldots\ldots\ldots (4)$$

The relation between the formula for well draw-down presented here with the one used by THEIS [1941] can be established by a simple change of variable. If, in the expression

$$s = (Q/4\pi KD)\int_{r^2/4\alpha t}^{\infty} (\epsilon^{-v}/v)\,dv$$

We make the substitution of variable

$$v = u^2$$

We obtain at once

$$s = (Q/2\pi KD)\int_{r/\sqrt{4\alpha t}}^{\infty} (\epsilon^{-u^2}/u)\,du$$

Eq. (4) is a form of the exponential integral [INGERSOLL and Others, 1948] which can be evaluated from tables [FEDERAL WORKS AGENCY, 1940; JAHNKE and EMDE, 1945] by use of the relation

$$\int_{r/\sqrt{4\alpha t}}^{\infty} (e^{-u^2}/u)\,du = -0.5\,\mathrm{Ei}\,(-r^2/4\,\alpha t) \qquad (5)$$

The draw-down produced in an aquifer of infinite extent due to a well pumped at the rate Q is given by (4). This expression is valid if s/D is small compared to unity.

We return now to (1) and set $r^2 = x^2 + y^2$. Then the flow of water across the line $x = x_1$ due to the withdrawal $Qd\lambda$ is obtained from the relation

$$\partial q_1/\partial\lambda = -\,KD\int_{-\infty}^{+\infty} (\partial^2 s/\partial x\,\partial\lambda)\,dy$$

$$= [2Qxe^{-x^2/4\alpha(t-\lambda)}/16\pi\alpha(t-\lambda)^2]\int_{-\infty}^{+\infty} e^{-y^2/4\alpha(t-\lambda)}\,dy \qquad (6)$$

The integral in this last expression is a form of the probability integral [FEDERAL WORKS AGENCY, 1941; JAHNKE and EMDE, 1945; PEIRCE, 1929]. This permits an evaluation of this expression in the form

$$\partial q_1/\partial\lambda = 2Q\alpha xe^{-x^2/4\alpha(t-\lambda)}/\sqrt{\pi}\,[4\alpha(t-\lambda)]^{3/2} \qquad (7)$$

To integrate this expression with respect to λ from $\lambda = 0$ to $\lambda = t$ set

$$v = x/\sqrt{4\alpha(t-\lambda)} \qquad (8)$$

Then, by substitution

$$q_1 = (Q/\sqrt{\pi})\int_{x/\sqrt{4\alpha t}}^{\infty} e^{-v^2}\,dv \qquad (9)$$

This can be expressed in terms of the probability integral

$$P(Z) = (2/\sqrt{\pi})\int_0^{Z} e^{-v^2}\,dv \qquad (10)$$

which has been extensively tabulated in terms of the upper limit Z. Then (9) can be put in the form

$$q_1/Q = 0.5\,[1 - P(x_1/\sqrt{4\alpha t})] \qquad (11)$$

This formula implies that there will be a drop in the ground water level along the line $x = x_1$. If a river exists at this distance from the well there will be no drop in level but, instead, the river will supply an additional flow to the well. These factors can be accounted for if a recharge well is placed at the point where the pumped well is imaged by the riverbank. A similar form to (11) would apply to the recharge well also, with the result that the flow across the line $x = x_1$ is doubled. Then the total flow across the line if the river maintains the level is

$$q/Q = 1 - P(x_1/\sqrt{4\alpha t}) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (12)$$

These results may be summarized as follows: The draw-down in an aquifer of infinite extent due to a well discharging at the rate Q is given by (4). This formula is valid, as a first approximation, if the draw-down s is small compared to the depth D. A similar well located at the distance x_1 from a river will draw the flow q from the river. The part of the total flow of the well which comes from the river is q/Q. The value of this ratio is given by (12).

Suppose we have three wells at distances of 1000, 5000, and 10,000 ft from a river, respectively, which have been pumped for a period of five years. It is desired to estimate the part of their flow which comes from the river. If the aquifer data are: D = 100 ft, K = 0.001 ft/sec, V = 0.2, $\alpha = KD/V = 0.5$, t = 157,770,000 sec, and $\sqrt{4\alpha t} = 17,763$; then the values for the three wells are as shown in Table 1.

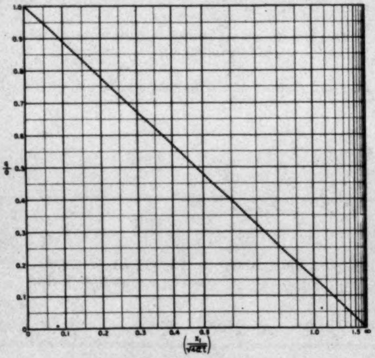

Fig. 1--The part of the well flow taken from the river as function of the parameter $x_1/\sqrt{4\alpha t}$

Table 1--Values for the three wells

Well	x_1	$x_1/\sqrt{4\alpha t}$	$P(x_1/\sqrt{4\alpha t})^a$	q/Q^b
1	1,000	0.0563	0.0635	0.9365
2	5,000	0.2815	0.3094	0.6906
3	10,000	0.5630	0.5741	0.4259

[a] From tables of the probability integral.
[b] From Eq. (12) or from Figure 1 directly.

Then at the end of five years the three wells are drawing, respectively, 93, 69, and 42 pct of their flow from the river.

While English units have been used here, the formulas given are valid when used in any consistent unit system. Such a system permits the use of only one unit of a kind. Since, in our case, only units of length and time are involved, change to another system of units can be accomplished by replacement of the foot and second units, used herein, with the new units.

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PRECIPITATION MEASUREMENTS ON WIND-SWEPT SLOPES

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Abstract--Precipitation catch for three calendar years is compared for four types of gage installation on a wind-swept south-facing slope with a 22° gradient at elevation 5500 ft. The 1950 precipitation catch by (1) weighing-recording gage with the orifice and an Alter type wind shield sloped parallel to the ground surface, (2) unshielded non-recording gage with orifice sloped parallel to the ground surface, (3) weighing-recording gage with horizontal orifice and Alter type wind shield, and (4) unshielded U. S. Weather Bureau standard gage with funnel removed was (1) 62.90, (2) 53.34, (3) 39.82, and (4) 27.64 inches, respectively. In 1951 the respective catches were (1) 61.38, (2) 52.94, (3) 35.91 and (4) 25.67 inches; and in 1952 they were (1) 39.62, (2) 35.01, (3) 27.09, and (4) 15.91 inches. Indications are that gage (1) probably did not overestimate precipitation amounts and that there is a relationship between wind velocity and magnitude of differences in catch between gages.

Introduction--The accurate measurement of precipitation is quite difficult. The problems encountered are increased by rugged terrain, exposure to wind, and the occurrence of a large proportion of the precipitation in the form of snow.

One of the principal causes of inaccuracy or variation in measuring precipitation on wind-swept slopes is the turbulence produced by the gage in the moisture-bearing wind stream. Some of the precipitation which should fall into the gage is carried over it because of an increase in pressure and consequent upward deflection of the air stream on the windward side and a decrease in pressure and marked acceleration of the air stream over the top of the gage [BROOKS, 1938a; KREIN, 1952].

The desirability of using wind shields to minimize air turbulence over a gage orifice has been demonstrated repeatedly. Relatively few of these studies were concerned with snow and still fewer included severe conditions of wind and topography. However, in almost every case it was shown that gage catch was materially increased by using a wind shield.

The Nipher [BROOKS, 1938b] and Alter [ALTER, 1937] types of shields have proved the most successful of the many types devised. The Nipher shield is the better of the two for rain but unsuited for snow when left unattended. The large flat surface collects snow which may later blow into the gage, or accumulating snow may bridge the receiver orifice. Slat-type Alter shields have been most successful for snow and are widely used on snow gages in the mountainous areas of the West [BERNARD and CODD, 1940]. The shield consists of sheet-metal slats loosely attached to a supporting ring approximately 40 inches in diameter. The apparent action of the shield is to close toward the gage and deflect the air stream downward enough to compensate for upward deflection caused by the gage [KREIN, 1952].

Another source of measurement error is the difference in angles at which the plane of the gage orifice and a sloping ground surface intercept precipitation. The error becomes large when precipitation falls at an appreciable angle from vertical into a gage with a horizontal orifice exposed on a steep slope. Tilting the gage improves the precipitation catch on slopes [STOREY and HAMILTON, 1943] because it intercepts precipitation on the same plane as the ground surface. The catch is then multiplied by the secant of the angle between the plane of the orifice and the horizontal to correct for slope and thus express precipitation on a horizontal basis. The same result can be obtained by cutting the gage orifice to the same angle as the slope, eliminating the need for slope correction. STOREY and HAMILTON [1943] suggested that this type of gage be called a "stereo" gage. They, with PAGLIUCA [1934], indicated that tilted gages are aerodynamically superior to stereo gages, however.

A number of gaging sites in a precipitation gage network on the Priest River Experimental Forest in northern Idaho are steep and exposed to winds. Gages developed for these more severe sites combine the advantages of stereo orifices and wind shields of the Alter type. Both the orifice and shield are parallel to the ground surface. Stereo orifices are used because some of the gages are of the weighing-recording type and not adapted to tilting. PAGLIUCA [1934] suggested slanting the gage and shield parallel to the slope for measuring snow, and HAYES and KITTREDGE [1949] used a tilted gage with Nipher shield for rain. The Priest River gage is thus essentially like the previously suggested forms but differs in using the slat-type shield which is better adapted to snow. As this combination is relatively uncommon, a test installation was operated for three years beginning in the fall of 1949 to compare the performance of this gage with three other types of gages. Early results of the test were reported by HELMERS [1952]. The concluding results are described below.

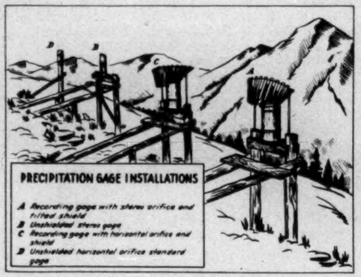
D
B
C
A
PRECIPITATION GAGE INSTALLATIONS
A Recording gage with stereo orifice and tilted shield
B Unshielded stereo gage
C Recording gage with horizontal orifice and shield
D Unshielded horizontal orifice standard gage

Fig. 1--Sketch of precipitation gage test installation

Gage installations and results--The gage installation (Fig. 1) was located at an elevation of 5500 ft on a windy south-facing slope with a 22° gradient, and included: (A) recording gage with stereo orifice and tilted shield, (B) unshielded non-recording gage with stereo orifice, (C) recording gage with horizontal orifice and shield, and (D) unshielded standard gage (8 by 24 inches non-recording) with horizontal orifice.

It is estimated that 50 pct or more of the annual precipitation at the test site occurs as snow. Gage orifices were all about ten feet above the ground surface to keep the gage bases just above the maximum snow-pack depth. Precipitation catches were usually measured weekly during precipitation periods but less frequently during 1952 and during the summer months of light precipitation.

Table 1 summarizes the annual catches for the three years of record. The differences in catch between gages are expected to vary between years due to differences in wind and in the proportion of precipitation falling as snow. In spite of these possible sources of variation in catch, the four gages ranked about the same in magnitude of catch during the two years of nearly equal precipitation. Precipitation for 1952 was roughly 40 pct less than for the previous two years and catches by the non-standard gages were from 10 to 30 pct higher as compared with the standard gage.

Table 1--Summary of 1950-1952 annual precipitation catch by four types of gage installation

Gage	Installation	Measured precipitation			Comparison with standard gage		
		1950	1951	1952	1950	1951	1952
		inch	inch	inch	pct	pct	pct
A	Recording gage with stereo orifice and tilted shield	62.90	61.38	39.62	228	239	249
B	Unshielded stereo gage	53.34	52.94	35.01	193	206	220
C	Recording gage with horizontal orifice and shield	39.82	35.91	27.09	144	140	170
D	Unshielded horizontal orifice standard gage	27.64	25.67	15.91	100	100	100

The rank in magnitude of annual catch was observed for practically every measurement period (Fig. 2). The principal exceptions were due to heavy snow storms when both stereo orifices became partially or completely bridged with snow. Other occasional exceptions were attributable to weighing errors or to very small storms, the total precipitation of which was near the limits of accuracy of the gage weighing devices.

The observed tendency of stereo gages to bridge earlier than the horizontal orifice gages tends to support the previously noted [STOREY and HAMILTON, 1943; PAGLIUCA, 1934] aerodynamic inferiority of stereo gages.

Gage catch was compared with snow-pack water equivalent to determine, if possible which gage was most efficient. These comparisons were not wholly successful, however. Rain and wind effects

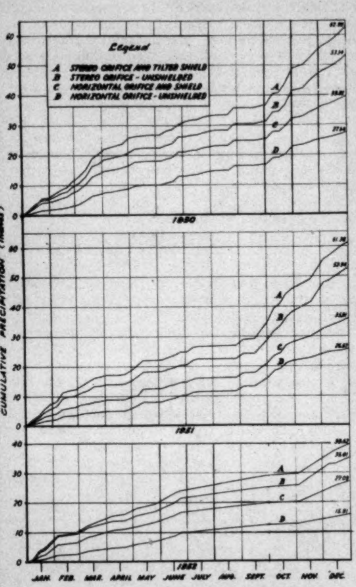

Fig. 2--Cumulative annual precipitation catch for three years by four types of gage installation on a wind-swept slope.

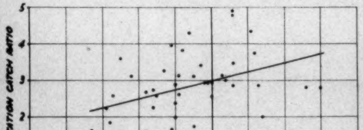

Fig. 3--Relationship of the precipitation catch ratio (catch by stereo gage with tilted shield to catch by unshielded standard gage) to mean weekly wind velocity

on the snow pack sometimes eliminated a sound basis for comparison. Apparent water equivalent gains were reliable only when there were no losses due to percolating rain or snow-melt water and when there was no wind erosion of snow. One of the more reliable comparisons of gage catch with snow-pack water equivalent gain includes the period from February 9 to March 8, 1950. Precipitation catch by the stereo gage with tilted wind shield was about 6.05 inches. The snow-pack water equivalent gain was 7.9 inches during the same period. March 23 to April 5, 1950, was another period of little wind erosion. The gage received about 2.8 inches of precipitation while the snow pack gained 3.2 inches of water. The gage orifice was about six feet above the snow surface on February 9 and March 23, and four feet on March 8 and April 5. These comparisons indicate that the most efficient gage of the four tested is probably the most accurate.

Gage catch consistently exceeded water equivalent gain in 1951. From February 2 to March 12 the gage accumulated 3.60 inches of precipitation but the snow pack gained only 2.4 inches water equivalent. The 1951 period, however, was windy as compared to the 1950 period as shown by Table 2.

Table 2--Comparison of daily wind travel during February 9 to March 8, 1950, and February 12 to March 12, 1951

Daily wind travel	February 9 to March 8,1950	February 12 to March 12,1951
mile	no. days	no. days
Less than 100	16	8
100 to 200	5	16
Over 200	0	4
No record	6	0
Total	27	28

During windier periods some wind-blown snow is very likely deposited in the gages at the same time that the snow pack is eroded. The gage orifice was about six feet above the snow surface during the 1951 period above.

Wind was recorded from a three-cup anemometer. This type of anemometer is unsuited to winter conditions and was often immobilized by snow, ice, and rime, resulting in fragmentary records. Available data, however, tend to support the observation of PAGLIUCA [1934] and others that the effectiveness of wind shields increases with increasing wind velocity. A significant (r = 0.39) relationship was found between mean weekly wind velocity and the ratio of the catch of the stereo-tilted shield gage to that of the unshielded standard gage with horizontal orifice (Fig. 3). The precipitation catch ratio of the first gage to the second (assuming the ratio is a linear function of mean weekly wind velocity, mph) was

$$\text{catch ratio} = 1.78 + 0.24 \times \text{mean weekly wind velocity, mph}$$

according to the best wind records available.

Summary--Precipitation catch for three calendar years is compared for four types of gage installations on a wind-swept south-facing slope at 5500 ft elevation. Precipitation catch by a standard eight-inch gage with a horizontal orifice was consistently low. The catch of a standard gage was increased by adding a horizontally mounted Alter type wind shield. Cutting the gage orifice to an angle equal to the slope gradient ("stereo-orifice") resulted in a greater catch, however, than adding a horizontally mounted wind shield. The greatest catch was obtained by a stereo gage with a windshield tilted parallel to the slope gradient.

Precipitation catch by the stereo gage with the tilted wind shield agreed well with snow-pack water equivalent gain during periods when wind did not erode snow cover or deposit drifting snow into the gages. Conclusive comparisons were not available, however. The stereo gage with tilted shield is presumed to be the most accurate of the gages tested.

The effectiveness of the wind shield increased with increasing wind velocity.

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THE TRANSMISSION OF WATER THROUGH SNOW

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Abstract--An instrument which makes use of the difference in the dielectric constants of ice and water was constructed and used to detect small changes in the liquid water present in a snow pack. The velocity of a moving front of water through snow and the approximate residual storage of liquid water in the snow pack was measured by means of this instrument. Water transmission rates were found to vary from 0.9 to 24.0 inches of snow per minute. The higher rates were associated with high density snow. The residual storage of liquid water in the snow varied between 0.7 and 5.5 pct with the majority of the measurements showing a residual storage of less than two per cent free water or about 0.1 inch of free water per foot of snow.

Introduction--The development and use of forecasts for runoff from snow-covered areas is complicated by the lack of reliable information on the liquid water storage and transmission capacity of a snow pack. The amount of melt water or rain which can be stored on a snow covered watershed and the rate at which the liquid water will be transmitted through snow and affect stream flow has been a controversial subject amongst hydrologists for many years.

More recently the military agencies have become interested in the amount of liquid water which may be retained in snow as it may influence trafficability, compactability, and other operations in snow-covered areas.

The question is not whether percolating water freezes at depths in the pack where temperatures may be below 0° C, but whether appreciable amounts of the liquid phase can be held by surface or capillary tension, or otherwise retained in a snow pack, isothermal at 0° C.

HORTON [1941] reports the retention of 0.6 inch of rain by a six-inch snow blanket of 0.1 density. This implies a water-holding capacity of 50 pct by weight of wet snow. It is possible that his observations were made under conditions which permitted impounding at the soil surface and backing up of the rain water into the voids in the snow. GERDEL and CODD [1945], studying the detention of rain in a new fallen snow, found that during and immediately following the precipitation period the new snow pack of 0.10 density held from 12.8 to 19.3 pct liquid water where topography and the nature of the underlying surface did not impede percolation. This is equivalent to about 0.15 to 0.20 inch of liquid water per foot of snow. The relatively high detention capacity was of a temporary nature since four hours after the cessation of rain the new snow pack contained only 1.5 to 5.0 pct free water. During the same precipitation period the liquid water content of an old snow layer of 0.38 density and several feet thick, beneath the new snow, varied between 0.4 and 5.9 pct, equivalent to 0.02 to 0.27 inch of liquid water per foot of snow.

LINSLEY, KOHLER, and PAULHUS [1949] report that new snow may be able to retain large volumes of rainfall for a brief period and then release it suddenly. Citing an unpublished report by Gerdel they describe the effect of 2.5 inches of rain which fell over a period of 60 hours on a ten-foot deep, new snow pack near Norden, California, in December, 1945. No increase of flow in a nearby stream was observed until about 58 hours after the beginning of the storm but the stream crested five hours after the first rise was noted which was about three hours after the end of the precipitation period.

HIMMEL [1951] presents the results of some studies on the application of artificial rain to a six-foot deep, midwinter snow pack of 0.35 density. During the experiment 29 inches of rain was applied at the rate of approximately 0.9 inch per hour. The ultimate discharge rate which was attained about four hours after the start of rain was equal to the rate of application and at that time two inches of rain was in storage or in transit through the pack. When the application of the artificial rain was discontinued the runoff record indicated that most of the water in transit or temporary storage drained out in two hours. The temporary impounding of water above the ice planes or consolidated crusts in the snow has been reported by GERDEL [1948]. Such storage capacity is of transient nature since the ice planes in wet snow rapidly disintegrate. Both vertical and horizontal internal drainage channels develop rapidly in a seasonal snow pack under the action of solution and hydrostatic pressure. The vertical channels are similar to the "pipes" or "ice glands" which develop in the firn snow on a glacier. These channels operate much like the rock drains sometimes used in construction and agricultural drainage practice where coarse material is buried in trenches, or filled in vertical bore holes to conduct water through more impervious material.

In contrast to soil, the snow pack is in a continuous state of metamorphism and the application of simulated rain to the snow surface may accelerate morphological processes conducive to marked changes in permeability. Under field conditions it is almost impossible to control the temperature of the air, the applied rain and the snow pack so as to prevent melting of the snow or freezing of the added water. During infiltration experiments change of state due to temperature differences may produce greatly misleading information on the infiltration capacity of snow. During the course of many experiments on the water-holding and transmission capacity of snow, the author has been unable to add water to the snow surface faster than it could be absorbed. In some of these studies water at 0°C was applied at rates in excess of eight inches of equivalent rain per hour.

The presence of natural flow zones within a snow pack is frequently indicated by a dendritic or pock-marked pattern on the snow surface. The pattern shown in Figure 1 is the product of subsidence of the snow surface above flow channels directed toward a small stream. A cross section through the snow at this site is shown in Figure 2. The dark areas indicate the flow zones through which melt water, dyed with fuchsine applied to the surface, is moving. The shaded vertical zones each underlie one of the depressions in the dendritic pattern illustrated in Figure 1. Near the

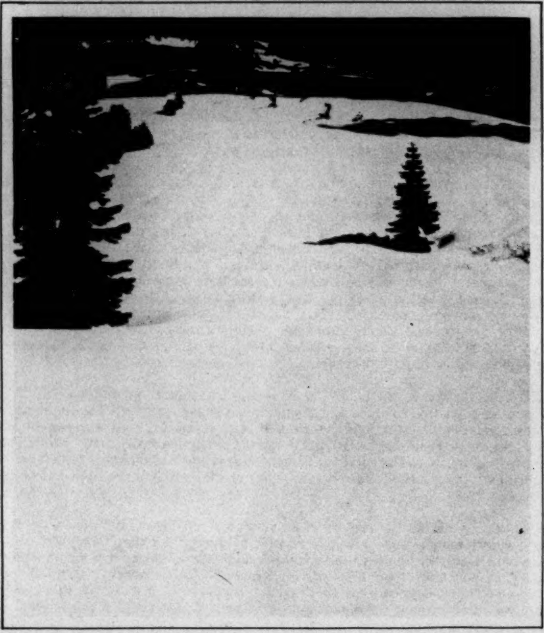

Fig. 1--Dendritic patterns on the snow surface indicating the presence of internal flow channels, pipes or glands in an actively melting snow pack; the pattern is the product of subsidence and not erosion

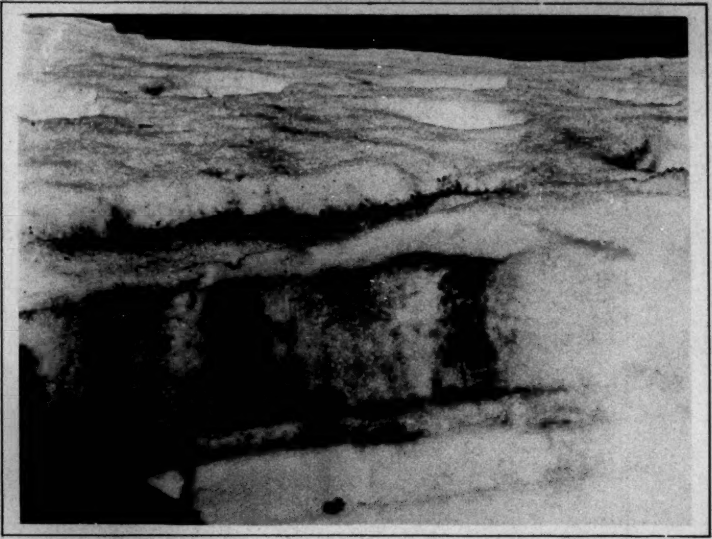

Fig. 2--A cross section through a small portion of the patterned area shown in Figure 1; the dark areas show how dyed melt water is moving internally through coarse grained glands which are similar to the rock drains used by engineers to improve subsurface drainage

stream the flow of melt water is channelized within coarse grained "glands" or above impermeable planes within the pack. It has been observed that buried crusts may be impermeable planes for a period and then become the chief horizontal flow zone as the ice bonds between the coarse grained crystals break down. The internal flow zones in a melting spring snow pack discharging water to a small stream are well illustrated in Figure 3. In this, as in all other photographs, the dark areas are the zones of concentration or flow of water, dyed with fuchsine. Except for the addition of a small amount of dye to the snow surface to identify and accentuate the location of the melt water within the pack, the natural snow was not disturbed nor was any water applied artificially at this site.

On more level areas the flow zones within the snow tend to develop as vertical pipes or glands. An exaggerated example of such phenomena is shown in Figure 4. The surface depressions which were later identified as vertical flow zones developed on the snow pack after the addition of about eight inches of water over four hours on an area of 1300 sq ft with a simulated rain making installation. The major subsidence occurred several hours after discontinuance of the simulated rain indicating that the pock-marks are the product of shrinkage as the water drains out of the flow zones.

Any assumption that a snow pack may hold 50 pct of free water by weight as cited by WISLER and BRATER [1949] implies that the highly permeable surface features do not extend to any depth in the pack or that the water accumulates above an impermeable layer such as an ice plane or a frozen soil surface, or that there are major obstructions to natural drainage. Snow may float on impounded water with a portion of its volume submerged. The saturated nature of the submerged portion is not a function of the detention capacity of the snow since, on removal from the water, free drainage would immediately reduce the liquid content of the snow to only a few percent of the total weight.

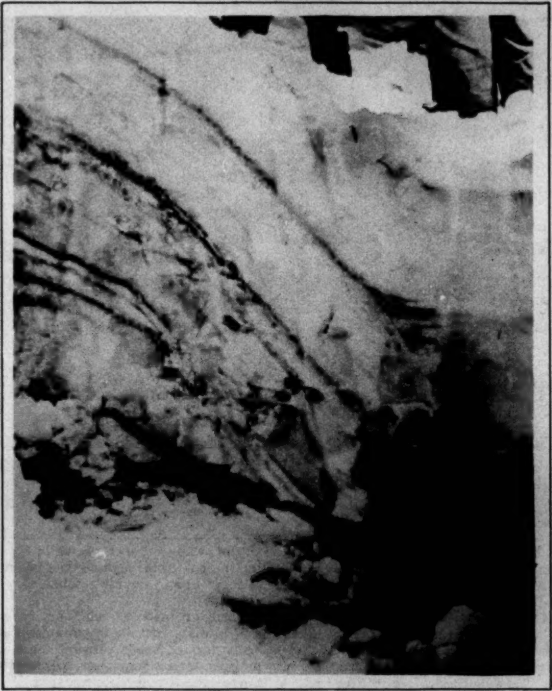

Fig. 3--Showing how the flow zones illustrated in Figures 1 and 2 continue, within the snow, to the nearest stream which is the dark area in the lower right corner of the picture

Instrument development--Studies on the movement of liquid water in snow are complicated by the lack of satisfactory methods for measuring the non-frozen water content and difficulties associated with sampling techniques which distort the physical properties of the sample and destroy the sample site. In an effort to devise a technique suitable to the in situ measurements of liquid water in snow, consideration was given to the design of an instrument which would make use of the difference in the dielectric constants between the solid and liquid phases of water.

The comparatively high dielectric constant of water has been used as the basis for the development of numerous types of meters for measuring the moisture content of such materials as grain [FLETCHER, 1939] and [HARTIG and SULLIVAN, 1933] bales of cotton [FLETCHER, 1939], wood [DUNLAP, 1937] and soil [FLETCHER, 1939]. ALEXANDER, SHAW, and MUCKENHIRN [1937] constructed an instrument for the dielectric measurement of the freezing point of water.

At 0°C the dielectric constant for water is 88.3 and for ice it is very close to 3.0 and for air 1.0 at frequencies above one megacycle. A very small amount of free water should produce a measurable difference in the dielectric constant of snow which is basically a mixture of ice crystals and air.

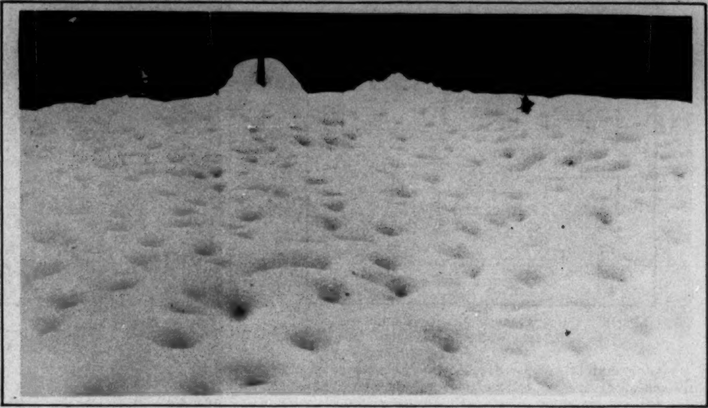

Fig. 4--The pock-marked surface was produced by the application of two inches of rain per hour for four hours; each depression is the surface indication of a vertical flow channel similar if not identical to the firn pipes or ice glands with which many glaciologists are familiar

On a purely empirical basis the dielectric constant of a unit volume of snow would be equivalent to the sum of the products of the volume of each constituent, air, ice, and water times the dielectric constant of the constituent, which may be expressed

$$\epsilon_s = (\epsilon_i V_i) + (\epsilon_w V_w) + (\epsilon_a V_a)$$

where

ϵ_s = dielectric constant of snow
$\epsilon_{i,\,w,\,a}$ = dielectric constants of ice, water, and air
$V_{i,\,w,\,a}$ = volume of ice, water, and air

By substitution in this equation it can be shown that a dry snow of 50 pct density would have a dielectric constant of 2.0. The presence of one per cent free water would increase the dielectric constant to 2.4, and five per cent free water would produce a dielectric constant of 4.1.

Preliminary experiments indicated that the change in dielectric constant induced by small amounts of water in snow produced sufficient change in capacitance to be detectable when snow samples were placed between the stainless steel plates of a condenser controlling the frequency of an oscillator. After the most suitable working range was determined, a resonance type capacitance meter, sensitive to very small changes in the free moisture content of the snow, was constructed for the author by John D. Bridges, an electronic engineer in Sacramento, California. The block diagram of this instrument is shown in Figure 5. It is essentially a beat frequency oscillator operating at about 1.5 megacycles. The frequency of one oscillator is varied by changes in the capacitance of the parallel plate probe inserted in the snow and the second oscillator is brought into resonance by means of a manually operated precision condenser equipped with a vernier dial. Resonance is indicated by a null meter.

One of the probe condensers for insertion in the snow is illustrated in Figure 6. The stainless steel plates are six inches in length, and 0.75 inch wide. The center plate is covered with a thin molded plastic coating to reduce the effect of electrical conductivity between the plates. The field instrument with five probes connected through a low capacitance switch unit to the meter is shown in Figure 7.

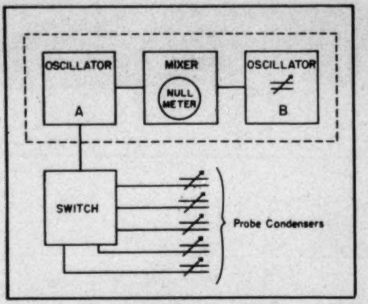

Fig. 5--Capacitance meter for the detection of free water in snow

Unfortunately, neither dry snow nor a mixture of snow, air, and water are perfect dielectrics. The size, shape, and axial orientation of the crystals which make up the matrix of a snow pack contribute to a phase defect which is difficult to measure. Since the apparent capacitance values indicated by the meter are produced not only by changes in the free water content but also by the pack density and the size of the crystals, the instrument must be directly calibrated in terms of the volume of free water present for each type of snow under study. Satisfactory calibration is difficult since no other reliable precision method for measuring the liquid water in snow is available.

For the most part calorimetric procedures for the determination of free water in snow, when used in the field under the most ideal conditions, cannot be expected to produce reliable data for liquid water in amounts less than two per cent. Since the water-holding capacity of a spring snow is in the order of one to five per cent the error in the vacuum bottle calorimeter method may be greater than the quantity of liquid water present. The capacitance meter readily detects the presence of water in the snow in amounts of a fraction of one per cent. It is not possible to produce a uniform artificial mixture of snow and water with a known low free water content to serve as a standard and since no satisfactory precision method for measuring the liquid water present in a natural snow cover is available it has not been possible to calibrate the meter for all snow types.

Fig. 6--The snow-probe capacitor used with the snow-moisture capacitance meter

When several of the probes are inserted in a pack of uniform physical composition and a small amount of water is applied to the surface of the snow the flow of water past each probe and the time for the water to move between several probes can be measured if the flow zone in the snow pack is first identified by a water-soluble dye, which has little effect on capacitance, conductance, or change in the melting point of snow. The use of dyes to identify flow zones and to trace the path of melt water and rain water through snow has been described in a previous paper [GERDEL, 1948].

Experimental procedure--Having determined that the capacitance meter could detect very small changes in the free water present in snow a series of experiments was organized to measure, if possible, the rate of transmission of water through snow.

The research site at the Sierra Snow Laboratory near Soda Springs, California, used for these studies consisted of a four- to eight-foot deep snow pack covering gently sloping ground which had

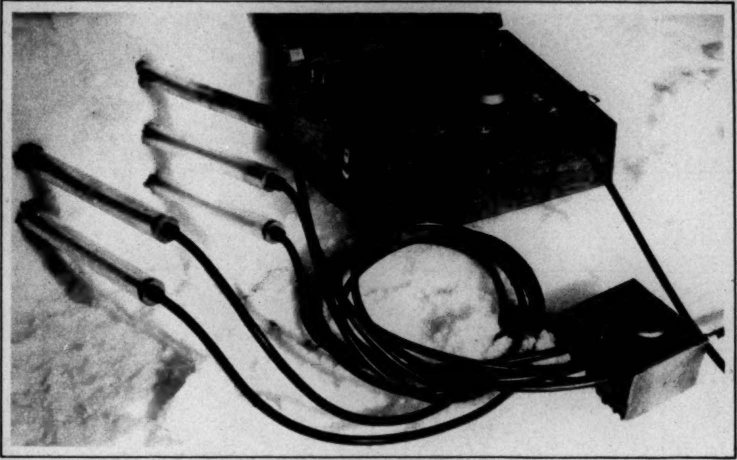

Fig. 7--The snow moisture capacitance meter equipped with five probes and switch box

good internal and surface drainage to a nearby stream. During a period in May, 1948, when the snow pack had become isothermal at 0° C and active melting was taking place a small amount of fuchsine dye was scattered over about two square feet of the snow surface. Twenty-four to 48 hours after the application of the dye the path of the melt water through the snow was determined by excavation and careful exposure of a profile and the probe condensers inserted in the identified flow zone. The method of inserting the probes at selected points in the flow zone is shown in Figure 8.

After recording the initial dial reading on the capacitance meter a measured amount of water at 0° C was rapidly and uniformly applied to the snow surface where the dye had originally been placed and the probe values read at stop-watch intervals as rapidly as the capacitance meter could be balanced and the probe switch operated.

During the course of each experiment several samples were removed from the dyed zone adjacent to one of the probes for determination of the free water content by the calorimetric method described by BERNARD and WILSON [1941]. The calorimeter values were used to prepare an approximate calibration curve for the capacitance meter and the snow type being studied. Reference to the calibration curve provided some indication of the magnitude of change in the free water content of the snow pack during the course of the experiments.

Each observation was made in a freshly excavated pit on selected horizons of visually uniform structural characteristics. No probes were placed nearer to the snow surface than six inches in order to provide the operator with sufficient time to obtain the peak reading after applying the water to the snow surface. Because flow rates were rapid, usually not more than two or three probes could be operated during a single experiment. Except for one experiment which will be discussed later, water was not applied nor were dielectric measurements made twice on the same profile.

Although a few studies were made of the horizontal flow rates no conclusive information was obtained from the very limited observations. The data and results reported herein are confined to the measurements of vertical flow.

From the data obtained in these experiments the transmission capacity of the snow was computed from the time interval between peak flow past each probe and the thickness of the horizon between the probes.

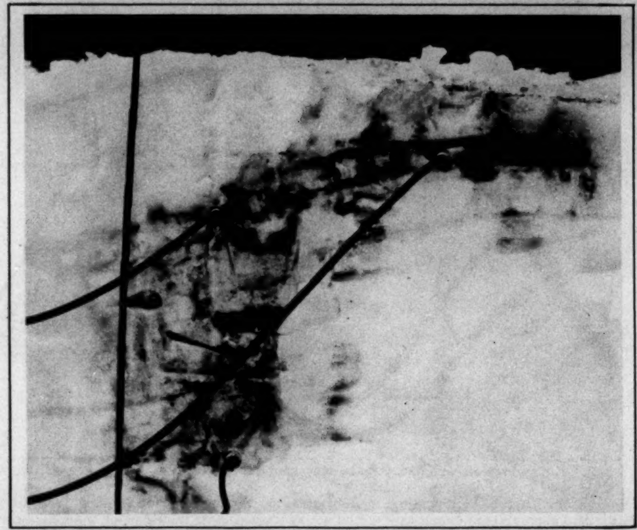

Fig. 8--The capacitor probes were placed in flow zones in the snow pack previously identified with fuchsine dye; this photograph illustrates one of the few experiments in which efforts were made to measure both horizontal and vertical flow of water through snow

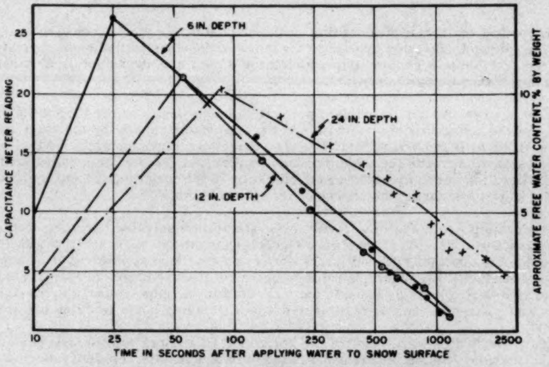

Fig. 9--Water movement through snow of 0.46 density as measured by the change in capacitance

The graphic presentation in Figure 9 of the data obtained from one of the experiments effectively illustrates not only the sensitivity and response of the instrument to rapid changes in the liquid water content of the snow but also how very rapid the actual change may be.

The water transmission rate for a snow pack as discussed in this paper may be considered as analogous to the travel time for a flood crest through a specific reach of a stream. When the water in transit through the snow pack is the product of surface melt, a deep snow cover of 6 to 20 ft such as is common in the western mountains will have within it, a diurnal wave of moving water which is an extension of the diurnal wave characteristic of the hydrograph of snow fed streams. The same analogy with adjustment for the time element applies to storm rainfall moving through a snow pack.

Discussion of results--The transmission rate for water through snow as measured by the change in capacitance produced by a moving front of water varied between 0.9 and 24.0 inches of snow per minute for 11 measurements as shown in Table 1. From these experiments, conducted on snow packs of 0.35 to 0.46 density, it appears that high transmission rates are associated with high density. OESCHLIN [1939] reported that low density snow had the higher transmission rate. His experiments were performed by measuring the moving front of fuchsine-dyed water through columns of new and compacted snow whereas the studies with the capacitance meter were conducted on a spring snow pack which had achieved high density through natural metamorphic processes. A coarse-grained natural spring snow pack of high density has a much different structure and greater permeability than an artificially compacted new snow of the same density. The higher rate of transmission through higher density snow indicated by the in situ measurements with the capacitance meter is compatible with the accepted idea that the maximum rate of discharge from a melting snow pack does not occur until it becomes ripe. Although "ripeness" is difficult to define, it is the product of morphological processes which convert the fine-grained residual winter snow cover to a coarse-grained pack of comparatively high density. The density of a ripe pack, however, is not an invariant. In a previous paper [GERDEL, 1948] it was pointed out that density values between 0.25 and 0.56 have been reported for ripe snow packs in the literature on snow hydrology.

Table 1--Transmission of water through snow

Snow density	Probe spacing	Water applied	Transmission rate[a]	Free-water content of snow[b]			Duration of observation
				Initial	Peak	End	
gm/cm^3	in	in	in snow/min	pct	pct	pct	min
0.35	25	2.0	1.1	4.0	16.2	5.5	19
0.35	41	2.0	1.1	1.4	9.3	1.1	19
0.40	7	0.8	0.9	3.8	6.2	1.1	18
0.40	17	0.5	3.7	4.1	6.2	1.7	18
0.46	6	2.0	12.0	6.0	10.7	5.1	48
0.46	12	2.0	16.0	4.0	9.8	0.9	48
0.46	18	2.0	18.0	4.0	10.3	0.9	48
0.46	6	2.0	24.0	5.0	10.3	2.6	35
0.46	12	2.0	24.0	2.9	10.3	0.7	35
0.46	6	2.0	24.0	3.0	10.3	2.0	35

[a] Computed from time interval between peak flow and spacing of capacitor probes.

[b] Interpolated from calibration curve derived from capacitance readings and calorimeter measurements on three or more snow samples collected during each experiment.

The rapid transmission of the applied water through the snow and the low free-water content of the pack at the end of the experiments, as shown in Table 1, indicate that a ripe snow will not retain much more than two per cent liquid water for more than a few hours. A liquid water retention capacity of two per cent in a ripe pack of 0.4 density is equivalent to about 0.1 inch of water per foot of snow, about the same as the field moisture capacity of a sandy soil.

It is apparent from this study that the concept of a snow mantle being a great sponge, capable of absorbing and withholding large amounts of rainfall [WISLER and BRATER, 1949] must be revised. Instead of being a sponge, the snow pack is more like a coarse sand in its capacity to hold or transmit water, except that the transmission constant and field capacity of a sand profile will vary little from time to time whereas the transmission capacity of snow may increase with each successive rain or unit of melt water moving through the pack. This increase in porosity of the snow is shown in Figure 10.

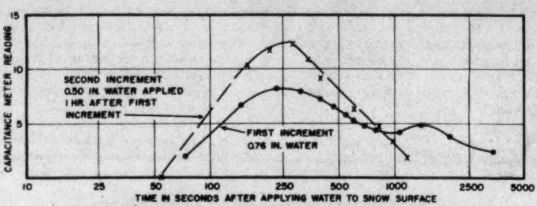

Fig. 10--Effect of successive additions of water on the transmission capacity of the snow pack; capacitance probe 18 inches below snow surface.

The data plotted in this figure were derived from a snow profile about 18 inches thick which was initially laminated with several wind or sun crusts buried beneath snow layers from subsequent storms. A single probe was placed at the bottom of this stratified profile which had an average density of 0.40. About 0.75 inch of water at 0°C was applied to the snow surface and the change in capacitance measured at stop-watch intervals. One hour later a second increment of water amounting to 0.5 inch was applied to the snow and the change in capacitance again measured.

The undulation in the depletion portion of the curve for the transmission of the first increment of water through the snow indicates temporary impounding and the subsequent disintegration of the less permeable crusts as morphological changes take place in the presence of free water. The curve for the second increment of water indicates that a more uniform porosity has developed as a product of the movement of the first unit of water through the pack. The crusts which temporarily impounded or retarded the flow of the first increment of water may have been the product of wind packing or of cyclic freezing and thawing of a snow surface which was later buried by subsequent storms. The crusts are usually so thin, compared to the balance of the horizon with which they are associated, that they have little effect on the measured density although the actual density of the impermeable film is close to that of ice.

Whether subsequent additions of water would have produced a further increase in porosity was not determined. At the termination of this experiment the 18-inch layer of stratified snow did not have the structural appearance of a uniform, coarse-grained, ripe snow pack although the drainage channels were as well developed as those commonly observed in ripe packs.

Preliminary planning of these studies had included the possibility of collecting sufficient data which would permit the application of Darcy's law and the determination of a permeability constant for snow, particularly for a ripe spring snow pack. It soon became apparent that even a ripe snow, actively discharging melt or rain water, was not a static, homogeneous porous medium. Horizons of almost undiscernible variations in texture and structure continue to undergo metamorphic processes which lead to a continuing increase in the rate of water transmission. Wind and solar crusts, so thin that they might be ignored or overlooked in describing and classifying the snow profile, may have a marked temporary influence and a minor over-all effect on the transmission capacity of a snow pack. Efforts to apply water at high rates over a sufficient area to provide reliable values for head differentials resulted in the rapid disintegration of the surface and internal structure of the snow pack. Inability to obtain suitable data for the derivation of a permeability constant further substantiates the high transmission rates actually measured.

Summary--An instrument designed to detect variations in the dielectric capacitance produced by changes in the amount of liquid water present in snow has provided a useful tool for the study of water movement through the snow pack.

Studies undertaken with this instrument on the rate of movement of water applied to the snow surface indicate that the transmission rate for snow of 0.35 to 0.46 density may vary from 0.9 to 24 inches of snow per minute. The higher transmission rates appear to be associated with high density and a ripe pack structure.

The transmission rate may increase with successive additions of water to the surface of the snow.

A snow pack may have a very temporary high water storage capacity pending the development of flow channels within the pack or over the ground beneath the pack and the satisfaction of the field moisture capacity. Drainage glands or pipes develop within the pack and flow channels develop at the contact with the ground surface very rapidly. The ultimate field moisture capacity of a ripe snow pack is about 0.1 inch of water per foot of snow.

When the drainage network is established within the pack and its field moisture capacity is satisfied, the discharge of melt or rain water will be approximately equal to the rate that the liquid phase is available at the surface of the snow.

Hydrologically a deep snow pack is effectively a pattern of small, temporary tributaries supplemental to the normal drainage network of a basin.

Acknowledgment--The instrument described in this paper was developed in its first stages by the author in 1944 when he was employed by the U. S. Weather Bureau and assigned to the U. S. Weather Bureau - University of Nevada Cooperative Snow Research Project at Soda Springs, California. Although the instrument was developed, financed, and constructed as a personal project by the author and John Bridges of Sacramento, free use was made of the facilities at Soda Springs for testing the meter during the development stage.

The studies on water movement through snow with this instrument were conducted in 1948 in the Central Sierra Snow Laboratory operated jointly by the U. S. Weather Bureau and the Corps of Engineers. They were carried out for the most part on personal time to test the instrument during the development stage and to check some personal ideas regarding the ability of snow to hold or transport water during periods of heavy rain.

The author is indebted to B. Lyle Hansen, formerly Director of the Central Sierra Snow Laboratory, and John D. Bridges, Sacramento, California, for material assistance in the development and construction of the final model of the capacitance meter. He acknowledges his indebtedness to the Snow, Ice, and Permafrost Research Establishment and the Snow Investigations Section, South Pacific Division, Corps of Engineers, for the permission to prepare this paper and for the use of facilities and material essential to the preparation of several of the figures used in this paper.

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ACTIVITY OF PARICUTIN VOLCANO DURING THE YEAR 1952

Carl Fries, Jr., and Celedonio Gutierrez

(Publication authorized by the Director, U. S. Geological Survey.)

Lava emission at Parícutin Volcano came to an abrupt end early on February 25, 1952, just 4 1/2 days after the Volcano's ninth anniversary. Explosive activity in the crater declined just as abruptly on the same day and continued only as intermittent, weak, noiseless puffs until March 4, when all activity came to a complete halt. In the 15 months between March, 1952, and June, 1953, when this paper was written, no further activity occurred either in the crater or at the lava vents; and in the opinion of the writers, renewed eruptions are unlikely.

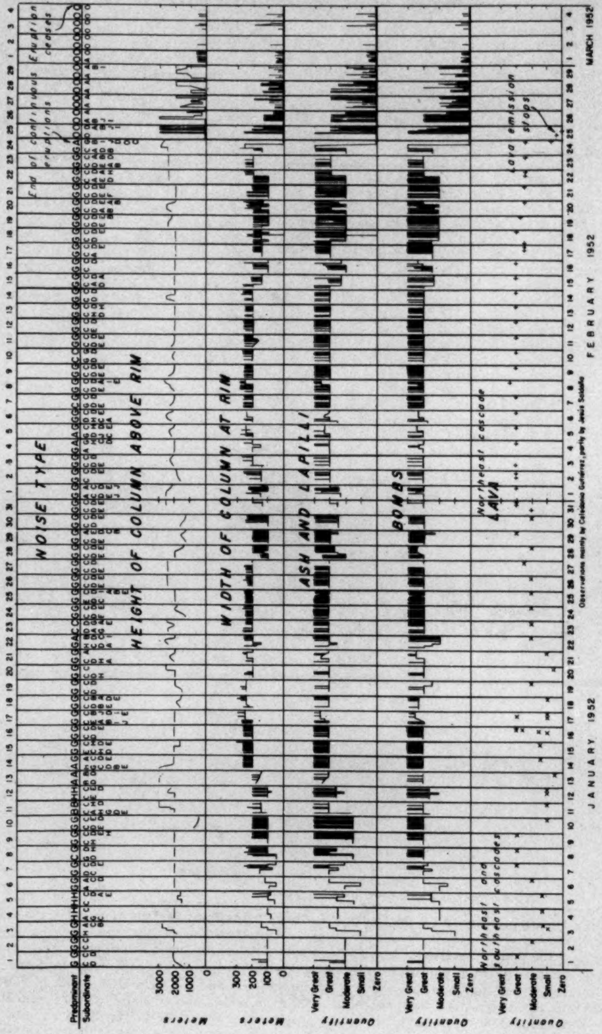
During the Volcano's brief final period of activity early in 1952, not only lava and ash eruption, but also explosive activity continued to increase notably over the period previously described [FRIES and GUTIÉRREZ, 1952b]. The trend toward increased activity had already been well established in the second half of 1951 [FRIES and GUTIÉRREZ, 1952b, p. 725], when the earlier continuous decline in activity was first definitely interrupted. Rainfall for the year 1952 was also greater than that of the year before, although this increase had no close relationship to the activity of the Volcano. The cessation of all activity on March 4 provided the opportunity to check the relationship of rainfall to intensity of activity and also the validity of the ashfall records of previous years.

The activity of Parícutin Volcano in the first three months of 1952, as well as observations on rainfall, ashfall, weather conditions, and other events in the vicinity throughout the entire year, was recorded by the junior author and his assistant, Jesús Saldaña, who maintained living quarters at Cuezeño camp. Their data on eruptive activity are given in Figure 1, and their observations on weather and ashfall are presented in Table 1. The monthly advance of the lava, as mapped by Gutiérrez, is shown in Figure 2. The senior author, who was at Parícutin on January 27-30, April 29-May 1, and November 4, for a total of eight days during the year, prepared the remaining tables and figures presented in this report and assembled and evaluated the material for publication.

Table 1--Monthly summaries of weather observations, rainfall, and ashfall near Parícutin Volcano in 1952

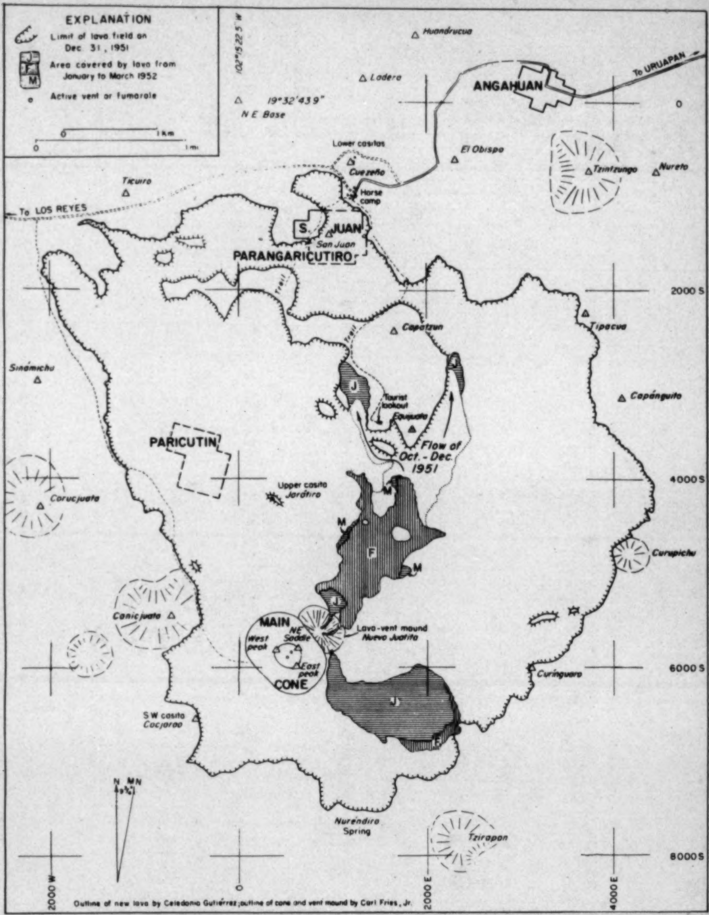
Month	Cuezeño station							Average direction of upper winds	Equijuata station	
	Temperature		Rainfall		Ashfall		Minimum humidity		Rainfall (total)	Ashfall (total)
	Max.	Min.	Total	Max.	Total	Max.				
	°C	°C	mm	mm	mm	mm	pct		mm	mm
January	27	0	0.0	0.0	1.3	0.5	24	SE	0.0	2.4
February	28	1	26.7	25.0	1.9	0.5	25	SW	23.2	8.3
March	. . .	1	0.0	0.0	0.0	0.0	20	. . .	0.0	0.0
April	. . .	5.5	26.6	12.0	0.0	0.0	13	. . .	43.2	0.0
May	. . .	6.5	184.7	46.5	0.0	0.0	22	. . .	102.3	0.0
June	26	8	247.4	46.5	0.0	0.0	40	. . .	284.7	1.0[a]
July	23.5	8	367.4	62.0	0.0	0.0	56	. . .	343.0	0.0
August	24	8	378.1	46.8	0.0	0.0	49	. . .	435.2	0.0
September	25	8	365.4	34.5	0.0	0.0	47	. . .	391.5	0.0
October	25.5	5	34.9	21.5	0.0	0.0	14	. . .	100.5	0.0
November	26	3	61.1	21.8	0.0	0.0	29	. . .	40.0	0.0
December	24.5	1.5	16.2	10.6	0.0	0.0	36	. . .	18.0	1.0[a]

[a] Accumulated in gage after cessation of eruptions and since last increment recorded in column.



Observations mainly by Celedonio Gutiérrez, partly by Jesús Saldaño

Fig. 1--Eruptive characteristics of Paricutin Volcano from January 1 to March 4, 1952


EXPLANATION
Limit of lava field on Dec. 31, 1951
J F M
Area covered by lava from January to March 1952
Active vent or fumarole
0 1 km
0 1 mi
102°15'22.5"W
19°32'43.9"
N E Base
Huandrucua
Ladera
ANGAHUAN
To URUAPAN
0
Lower casitas
El Obispo
Tzintzungo
Nureto
Cuezeño
Horse camp
Ticuiro
To LOS REYES
S. JUAN
San Juan
PARANGARICUTIRO
Trail
2000 S
Tipacua
Capatzun
Sinámichu
J
Tourist lookout
Equjuata
Capánguito
Flow of Oct.-Dec. 1951
PARICUTIN
Corucjuata
Upper casita
Jarátiro
4000 S
M
F
M
Curupichu
J
Canicjuata
MAIN
NE Saddle
West peak
Lava-vent mound
Nuevo Juatita
East peak
CONE
6000 S
Curínguaro
J
S W casita
Cocjarao
N MN
Nuréndiro Spring
Tzirapan
8000 S
2000 W
0
2000 E
4000 E

Outline of new lava by Celedonio Gutiérrez; outline of cone and vent mound by Carl Fries, Jr.

Fig. 2--Areas covered by Parícutin lava flows from January 1 to March 31, 1952

Activity of the cone--Details of the final eruptive activity in Parícutin crater are shown graphically in Figure 1, in which the lettered noise types shown in the diagram refer to descriptions in an earlier report published in these Transactions [FRIES and GUTIÉRREZ, 1951, p. 216]. The eruptive column reached a maximum height of 3000 m in both January and February, and its average height was about 2000 m, being thus greater, on the average, than during the preceding six-month period. Electric discharges within the ash column and from the ash column to the cone occured, as usual, during heavy ash eruptions.

Ashfall continued to increase in volume over the second half of 1951 and during January and February, 1952 (see Table 1) was about five times that of the first two months of 1951 [FRIES and GUTIERREZ, 1952a, Table 1]. For example, the total ashfall for January and February, 1952, was 3.2mm at Cuezeño station and 10.7 mm at Equijuata station, in comparison with 0.6 mm and 2.2 mm at those stations in January and February, 1951. A comparison of annual ashfall from 1947 to 1952 is presented in Table 2. The cessation of strong eruptions on February 25 corresponded with the cessation of the fall of newly erupted ash in the rain gages.

Table 2--Annual rainfall and ashfall at Cuezeño and Equijuata stations, 1947 to 1952

Period	Cuezeño station		Equijuata station	
	Rainfall (total)	Ashfall (total)	Rainfall (total)	Ashfall (total)
	mm	mm	mm	mm
1947[a]	1480.5	43.9	2411.4	129.2
1948[a]	1710.8	12.3	1893.2	45.6
1949[a]	1355.2	8.7	1593.9	16.8
1950[a]	1315.0	7.2	1761.5	11.6
1951[a]	1510.6	5.8	1600.8	15.1
1952	1708.5	3.2[b]	1781.6	12.7[b]

[a] FRIES and GUTIÉRREZ [1952b, Table 2].
[b] Ash was erupted only in January and February, 1952.

In order to resolve certain doubts as to the validity of the ashfall records given by the rain gages, which may have included ash lifted from the surface of the ground by the winds during the dry season, the records were kept for the ten months following the cessation of eruptive activity. Both the dry season and the rainy season, as well as the relatively dry months at the end of the year, fell within this period. The gage at Cuezeño station did not collect a measurable quantity of ash during this entire period. That at Equijuata station, however, which was not as well protected as the Cuezeño gage, accumulated a total of about two mm of ash in the ten months from March through December. The Cuezeño records may therefore be taken as indicating the true fall of newly erupted ash. The Equijuata records include a small percentage of wind-blown surface ash, but the maximum increment attributable to this cause was probably less than 20 pct for the year of minimum ashfall (1950) and was much less for other years.

The strong detonations characteristic of the last two years or so of the Volcano's eruptive history continued to increase in frequency; some 280 detonations were marked by the continuous-recording barograph during January and about 305 between February 1 and 25, 1952, when the strong eruptions ceased abruptly. This frequency contrasts with a total of about 400 such detonations in the entire second half of 1951. Bombs a few centimeters in diameter rose to heights of 1000 to 1200 m above the cone during the strongest of these explosions, in contrast to heights of 500 to 600 m during periods of ordinarily strong eruptive activity. Coarse pyroclastic material expelled by these intense explosions was so abundant that its fall on the flanks of the cone and near the base raised dust clouds that obscured the cone from view for some minutes at a time. Blocks of lava weighing more than 100 tons each were hurled from the crater and fell beyond the base of the cone.

Beginning on January 1 both crater vents [FRIES and GUTIERREZ, 1952b, p. 729] were active and of nearly equal eruptive intensity. At times the eruptions were simultaneous in the two vents and at other times they showed no relationship from one vent to the other. On January 23 the eruptions alternated from white vapor to black ash-laden vapors, but at other times such an alternation was not observed. In addition to ordinary explosions every five to 15 seconds, intense detonations occurred at intervals of 15 minutes to four hours, without exhibiting any recognizable periodicity.

On February 24, the last day of strong continuous eruptive activity, the ash eruption was of the type that first began on March 18, 1943, and ash rained down over the countryside in large quantities, especially northeast of the cone, where a gray curtain extended several kilometers from the Volcano. This eruption was apparently the final spasm of activity, for during that same night continuous activity came to a halt. Except for a few intense explosions the following day, eruptions occurred only intermittently until March 4, when activity ceased entirely.

The junior author's description of the last day of strong but discontinuous eruptions (February 25), as translated from his notes of that day, is as follows: "At dawn the crater of Parícutin Volcano is wholly without eruption -- without any noise and even without any vapor arising from it. It is very rare for such a drastic change to occur so shortly after such great activity, and for the Volcano to be completely dead. At 13h 00m a fantastically great volume of vapors again bursts forth in a cauliflower-like pillar from which great quantities of rock and ash are hurled, accompanied by the detonations of electric discharges. At 13h 30m the vapors cease and the crater becomes inactive. Five minutes later there appears another eruption, which lasts until 14h 00m. At 16h 00m another eruption, with a weak, deep-seated detonation, appears and ceases within five minutes. At 16h 15m another weak eruption arises in the form of an arborescent column of black vapors and ceases almost immediately. At 16h 30m a further eruption appears very weakly. At 17h 00m another weak eruption surges forth, and at 18h 30m some vapors arise without force. Each of these intermittent eruptions of a few minutes' duration arises without force and without noise, or with very faint sounds like the sighing of a strong breeze through the pine trees. At 21h 00m another weak eruption appears in the crater, which thereafter remains silent and without hurling out a single incandescent rock -- all visible pyroclastic activity has ceased."

On February 26 only weak intermittent eruptions occurred, carrying the vapor column to only about 1000 m above the cone. Activity ceased almost immediately after each eruption and the vapor cloud was carried away by the wind. Variable but small quantities of fine-grained pyroclastic material were hurled out. On February 27 the eruptions were similar to those of the preceding day, and the vapor cloud was dissipated in a few minutes. Periods of several hours passed without eruptions. On February 28 the eruptions came about once an hour, and only three out of ten of them carried any observable pyroclastic material. The vapors, which were yellowish and whitish, disappeared at a height of about 500 m above the cone, although those from the strongest explosions rose to nearly 2000 m. Similar conditions were observed on February 29. On March 1 small eruptions were observed at 06h 30m, 08h 00m, 09h 00m, 10h 00m, 12h 00m, 17h 15m, 18h 00m, and 19h 25m. On March 2 a small eruption occurred at 11h 30m, and on March 3 eruptions were recorded at 12h 15m, 17h 05m, and 17h 30m. On March 4 only two eruptions were seen, one at 06h 50m and another at 09h 15m. This last eruption was apparently the final one, for not a single eruption was observed thereafter. None of the eruptions after February 25 was strong enough to be marked by the continuous-recording barograph.

Form of the cone and crater--The final two months of activity in the crater had little effect on the general outward appearance of the cone (see Fig. 2 and 3). The northeast and southwest saddles and flanks were somewhat filled in and rounded out, and both peaks were further built up, as shown in Table 3 [compare with FRIES and GUTIÉRREZ, 1952b, Table 3]. The vertical changes were accompanied by small changes in the horizontal distances of the points reported. The highest point on the cone is the west peak, which is less than one meter higher than the east peak and about four meters lower than it was in August, 1951, owing probably to the frequent strong detonations during the last few months of the Volcano's active life. The two peaks rise about 410 m above the level of the original surface of Pulido's cornfield, where eruption first began on February 20, 1943. The base of the cone is oval and has a diameter of about 650 m from northeast to southwest and 900 m from northwest to southeast, but the crater rim is nearly round and has a diameter of some 280 m (see Fig. 2 and 4). The northeast saddle is only 79 m higher than the top of Nuevo Juatita lava-vent mound on the northeast side of the cone, and the southwest saddle is probably less than 70 m higher than the old lava-vent mound at the base of the cone on that side (see Fig. 3).

Table 3--Horizontal distances[a] from Cuezeño station, and elevations[b] above sea level, of points on Parícutin Volcano

Date	West peak		Lowest point on northeast rim		East peak		Lava-vent mound	
	Distance	Elevation	Distance	Elevation	Distance	Elevation	Distance	Elevation
	m	m	m	m	m	m	m	m
May 1, 1952	5230	2808.6	5170	2770.3	5370	2807.9	5000	2691.5

[a] Estimated accuracy of horizontal distances is within ten meters.

[b] Elevations determined by alidade from Cuezeño station; estimated accuracy of two meters.

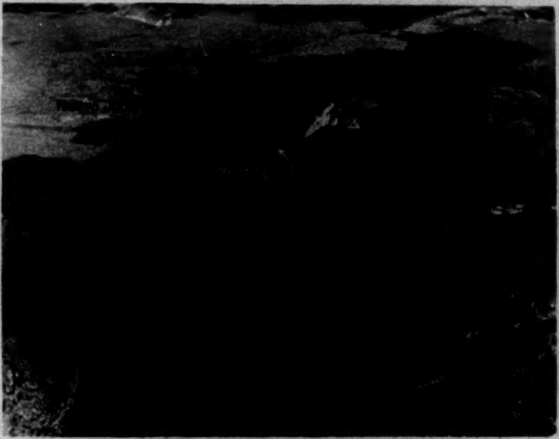


Fig. 3--Oblique aerial photograph of Parícutin Volcano on April 29, 1952, looking east; shows form of cone and crater rim, as well as lava-vent mounds at northeast and southwest base of cone

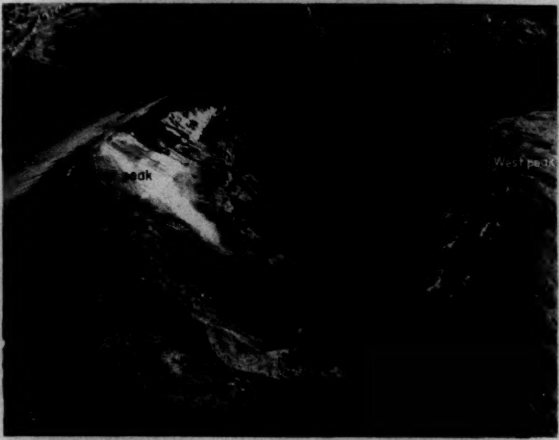


Fig. 4--Oblique aerial photograph of Parícutin cone and crater on April 29, 1952, looking southwesterly; both crater vents are clogged, and the southwest quadrant of crater wall is slumping into southwest vent; white snow-like crusts are NH_4Cl deposited by exuding vapors

The two crater vents are aligned in the usual northeast-southwest direction, as shown in Figure 4. The northeast vent seems to have had somewhat less intense eruptions in the last few weeks than the southwest vent, as its funnel is not as broad and its bottom is not quite as deep. The first ascent to the crater in 1952 was made by the junior author and his assistant, Saldaña, on March 8, four days after the last eruption. At that time the two vents were stopped up with blocks of reddish cemented rubble, which probably represented slumped material from the lower part of the interior of the crater. The bottoms were some 30 or 40 m below the northeast and southwest saddles. Steam rose lazily in small wisps from several concentric fissures around the south, southwest, and west sectors of the crater rim. The southeast and northwest interior slopes of the crater were partly covered with white and pale-yellow sublimates, similar to the sublimates of ammonium chloride with variable small quantities of iron chloride common on the flanks of the cone for some years and on the ash around fumaroles issuing from the new lava flows. No new or unusual type of sublimate was noted.

On April 29 the senior author chartered a small airplane in Uruapan and flew over the cone and lava fields in order to take pictures, two of which are reproduced in Figures 3 and 4. Fissures around the southwestern half of the crater rim are plainly visible in Figure 4, and the sublimates appear as remnants of snow. On the following days, the authors climbed to the top of the cone and the junior author could verify the further slumping of the interior flanks of the southwestern half of the cone, as shown in Figure 4.

On June 26 the junior author climbed the cone again and found the fissures to be further widened and lengthened, extending even into the east and west peaks. The bottom of the southwest vent had sunk and the interior flanks of the crater were slumping into it. The northeast vent was further filled with slumped material from the inner walls of the crater. Another ascent was made on August 14. The bottoms of the filled vents seemed to have continued to sink, and slumping of the inner flanks of the crater was further advanced. On November 5 the junior author and Saldaña, accompanied by B. W. Wilson, geologist of the U. S. Geological Survey, visited the crater to note any changes since the ascent in August. The fissures had continued to widen and lengthen, the interior flanks of the crater had continued to slump, and the two vent fillings seemed to have sunk even further. This sinking of the vent fillings probably caused slumping of the inner walls of the crater and is responsible for maintaining a nearly constant difference of elevation between the bottom and the rim of the crater.

Reports of eruptions after March 4 occurred from time to time in local newspapers, but continuous observations by the junior author and his assistant, as well as repeated trips to the top of the cone, confirmed the absence of any eruption after March 4. At 15h 15m on October 3, the junior author heard a loud subterranean noise as if an explosion had occurred under the cone, but this disturbance produced no detectable change on the surface of the cone or in the crater.

While earthquakes were seldom felt in the vicinity of Parícutin during the few years previous to the cessation of volcanic activity, many were felt in the months immediately after. Earthquakes were felt at Cuezeño on March 27 and 28, April 4, 5, and 11, May 18, 20, 21, 23, and 25, July 18, 21, and 26, September 18 and 25, and October 10. These were compared with the records at the Central Seismological Station in Tacubaya in the Federal District. Out of 33 shocks noted by the junior author at Cuezeño station in March and April, only six were recorded at Tacubaya. Three of these six had their epicenters at distances of 285 to 322 km from Tacubaya, and as the distance from there to Parícutin is about 320 km, the shocks probably had their origin at the Volcano. Tacubaya recorded three quakes on May 25 and one on October 10. None of these had their origin near Parícutin, however, but they were felt over a large area that included Parícutin. Many of the shocks felt at Cuezeño station were not recorded at Tacubaya, an indication that these quakes were only of local origin and were related to the Volcano. The authors thought that the strong local quakes in March and April might herald a renewal of eruptive activity, but, as the frequency of the quakes decreased later in the year, the danger was felt to be less imminent as time went on. The stronger shocks tumbled loose blocks on the surface of the flows and down the steep lava fronts, raising columns of dust. These shocks undoubtedly aggravated the slumping of the interior walls of the crater and possibly the sinking of the vent fillings. They did not, however, produce any major changes in the features of the cone and around the Volcano.

Activity of the lava vents--Only the Nuevo Juatita lava vent was active in 1952. The cascade of lava that began to flow toward the northeast on December 30, 1951, continued for only a few days (see Fig. 2), although on January 16 it again became active for a few days. On January 1 a new lava vent opened at the southeast base of the lava-vent mound and continued to supply lava until the end of the month, when the northeast cascade again became active. On February 8 a second northeast cascade formed and lava continued to flow from it in large volume until on the 22d of the month, the flow seemed to become sluggish on the surface. During the evening of February 24 the emission of lava declined abruptly, and on the morning of February 25 it ceased altogether, not to be resumed up to the time of writing this report (June, 1953). It has been pointed out in a preceding paragraph that the cessation of lava emission was accompanied by the cessation of continuous eruptions in the crater. The lava-flow fronts continued to move, of course, for some days after the flow of lava ceased at the vents.

On March 8 the area of the northeast lava vent was fissured and the reddish glow of hot basalt could be seen in the fissures, but there was no movement of the lava. After rainstorms in June, tenuous white vapors rose above the entire area of the vents, fissures, and the final lava flows. Such vapors after rainstorms continued for the rest of the year and were often quite dense. They consisted principally of steam formed by the action of the underlying hot lava on rain water that seeped down through the cover of ash and cooled lava. At the end of the year, intense heat was still being emitted by the lava-vent areas on the northeast and southwest sides of the cone.

Activity of the lava flows--The flow that moved northward from the cone, around the base of Equijuata, continued to advance early in January, although it was cut off at its source late in December, 1951. The tongue on the west side of Equijuata moved over old terrain at the base of Capatzun. The new flow that began to move southeast on January 1 reached the edge of the Parícutin lava field early in February and covered a little of old terrain. On February 8, 1952, new lava cascaded northeastward over the flows of 1951. The front of this new flow continued to advance sluggishly for a few days in March, even though the cascade was beheaded on February 25.

As shown in Table 4, the area covered by lava in the first two months of 1952 was 1,910,000 sq m. Assuming that the average thickness was eight meters, the total volume of lava extruded was 15,000,000 cu m, or some 270,000 cu m per day on the average. This was nearly three times the average daily volume of lava extruded during the second half of 1950 and the first half of 1951. We therefore see that both lava and ash emission increased notably in the last few months of the Volcano's activity. The total area covered by the lava field, including the cone itself, is now 24.8 sq km, in comparison with 22 sq km at the end of 1946 and 24.2 sq km at the end of June, 1950 [FRIES and GUTIÉRREZ, 1951, p. 220].

Table 4--Area covered by Parícutin lava in 1952, and estimated volume and weight of lava

Period	Days	Area covered	Estimated average thickness	Total volume for period	Average daily volume	Average daily weight
		thousand sq m	m	million cu m	thousand cu m	thousand met tons
Jan. 1 - Feb. 25, 1952	56	1910	8	15	270	520

Weather data--Winds began to raise dust from the dry ash surface in January, but no notable dust storms were observed until March 2, when the cone was obscured from view from Cuezeño station at times during the day. Several such days were repeated during March. May was an unusually wet month. Heavy rains fell on May 11, 20, and 22. Rainstorms occurred almost daily beginning May 31 and continuing through the summer. By July, new areas of forest and field were being washed clean of Parícutin ash, and crops developed better than formerly. Drainage changes took place frequently because of deposition or erosion of ash by the storm runoff. Harvests were better in August than in any year since the birth of the Volcano. The weather cleared in late September and was fairly dry during the rest of the year (see Table 1).

Total rainfall for the year at Cuezeño station was 1708.5 mm, an amount about equal to the 1948 total but considerably greater than that of any other year from 1947 through 1951 (see Table 2). Certainly the effect of eruptions from the Parícutin cone on the rainfall at Cuezeño was not particularly great and was outweighed by other factors. Although the general pattern of annual rainfall at Equijuata station was similar to that at Cuezeño station, the lack of relationship to eruptions is not so clear. Certainly some of the precipitated moisture near the cone was re-evaporated by the hot lava and returned to the atmosphere. This may have augmented the rainfall in the area, thereby causing the precipitation at Equijuata to be greater than at Cuezeño. The smaller excess of rainfall at Equijuata over that at Cuezeño in 1952 may be due in part to the cooling of the lavas and consequent decrease in re-evaporation near the cone.

Hot air and other gases continued to rise from the cone and the nearby lava fields in the months after cessation of eruption and on many days condensed over the cone before clouds formed elsewhere in the region. Usually the first clouds to form in the morning were almost directly above the cone, and later in the day the normal moisture clouds mingled with these to obliterate them as separate features. At times, people who saw these white clouds from a distance were certain that the Volcano was in eruption and thus spread rumors to that effect. Even as late as November, 1952, puffy white clouds formed at several hundred meters above the cone and lingered there after other normal clouds had evaporated. This phenomenon suggests that some water vapor was still rising from the cone and lava fields. Possibly the heat from the latest flows carried moist air up to the level where it condensed. Drainage from the north slopes of the high Cerros de Tancítaro, south of the cone, almost in its entirety flows out over Parícutin lava, and the evaporation of this moisture probably accounts in large part for the puffy clouds above the cone.

Acknowledgments--Observations were carried on cooperatively by the U.S. Geological Survey, under the auspices of the Technical Cooperation Administration of the Department of State, and the Instituto Nacional de Investigación Científica of the Mexican Government. In this respect, the valuable cooperation of Ricardo Monges López, Representative for Geological Sciences on the Board of Directors of the Instituto and also Director of the Instituto de Geofísica, is particularly appreciated. The help of the Instituto Nacional para la Investigación de Recursos Minerales in arranging for disposition of the observatory cabin at Cuezeño is acknowledged. This cabin, which was built by the Geological Society of America in 1944 and donated to the Mexican Government at that time, was taken over by the Comisión del Tepalcatepec in Uruapan and was moved in May, 1953, to Barranca Seca (Nuevo Zirosto), where it will be used as a schoolhouse. Continuous observations at Parícutin were abandoned at the end of June, 1953. Earthquake records at Tacubaya were furnished by Jesús Figueroa A., Chief of the Central Seismological Station in Tacubaya. The writers also mention the aid of Kenneth Segerstrom and Ray E. Wilcox in reviewing the manuscript, and of José Lauro Ramírez in drafting the illustrations. They hope that the brief descriptions of the Volcano's activity published over the years will be useful to geologists interested in volcanoes in other parts of the world.

As a befitting closure, the junior author, a lifetime resident of the area, wrote the following commentary in his diary on March 20, 1952: "Our Volcano of Parícutin is like a dream, in which we visualized the activity and fury of its eruptions for nine years and four days. That we actually saw it come into being, grow, and then die, seems to be completely unreal, but Parícutin's activity cannot be a dream, for the high mountain now present is an irrefutable witness before the world."

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GRAVITY SURVEYS OF CENTRAL PENNSYLVANIA

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(Contribution from the Division of Geophysics and Geochemistry, School of Mineral Industries Experiment Station, Pennsylvania State College.)

Abstract--Gravity surveys in central Pennsylvania were made in an attempt to obtain information which could be related to subsurface structures near the Allegheny Front. Results show no distinct relationship between gravity anomalies and major structural folding; however, they do indicate an intrusion or upthrust of the basement east of the Allegheny Front. It is believed that this basement feature was responsible for the forces causing the northwestward structural salient in the Appalachian Mountain of central Pennsylvania.

Introduction

A gravity survey consisting of six traverses was carried out in central Pennsylvania. The purpose of the gravity survey was twofold: (1) to obtain gravity data which would help to solve some of the geological problems along the Allegheny Plateau in central Pennsylvania; and (2) to obtain information which might be of value in oil and gas exploration.

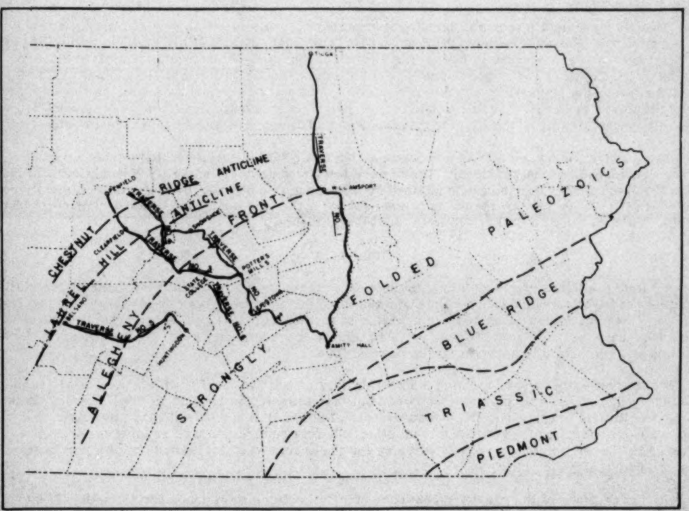
TIOGA
TRAVERSE
WILLIAMSPORT
NO. 1
RIDGE ANTICLINE
ANTICLINE
FRONT
PENFIELD
TRAVERSE
CHESTNUT
CLEARFIELD
HILL
TRAVERSE
NO. 2
SNOWSHOE
TRAVERSE
POTTERS MILLS
STATE COLLEGE
TRAVERSE NO. 4
LEWISTOWN
LAUREL
BELSANO
TRAVERSE NO. 3
HUNTINGDON
ALLEGHENY
STRONGLY
FOLDED
PALEOZOICS
BLUE RIDGE
AMITY HALL
TRIASSIC
PIEDMONT

Fig. 1--Index map of eastern two-thirds of Pennsylvania showing gravity traverses and major structural trends in the central portion (one inch equals approximately 46 mi)

Principal problem was an attempt to determine the probable relationship of the basement rock to the folded sediments in the neighborhood of the Allegheny Plateau.

Four gravity traverses were made across the Allegheny Front (traverses 1, 2, 3, and 5 of Fig. 1). Traverse 4 was made on the Allegheny Plateau so as to cross the Laurel Hill Anticline and traverse 6 crosses the Stone Valley Synclinorium in the Valley and Ridge Province to the southeast of State College. Figure 1 also shows the main structural features of central Pennsylvania.

Geological and geophysical history of the area

There are a number of theories pertaining to the origin and cause of the forces which resulted in the folding of the Appalachian Mountains. It is generally conceded that the main force came from southeast of the area; this is borne out by the diminishing intensity of the folding to the northwest as well as by the asymmetry of the folding.

Little is known of the configuration of the Precambrian basement complex or what part it played in the deformation. If we assume that the basement complex consists of metamorphics and metasediments intruded by igneous rocks, the problem is complex. This is especially so as there are no outcrops of the Precambrian in the central part of Pennsylvania where this survey was carried out. In addition to the probable complexity of the basement, there are undoubtedly numerous intrusives of later age, such as the peridotite in Indiana County [HONESS and GRAEBER, 1924], which is probably of Triassic Age.

In general, there are two principal theories concerning the role the basement complex played in the deformation: the first is that the basement was warped concordantly with the overlying sediments and the second is that the basement was not involved in the folding, that is, the sediments moved horizontally (slid) across the basement. It is most probable that the actual case lies somewhere between these two extremes.

That the basement was probably warped considerably, especially in some areas, is borne out by the Airborne Magnetic Survey [PIRSON and BACON, 1947; JOESTING, KELLEY, and KING, 1949] made in central Pennsylvania in 1946. The results of that survey show quite distinctly that the trends of the Chestnut Ridge and Laurel Hill anticlines coincide with magnetic anomalies. In this area, however, the magnetic picture is considerably distorted by polarization anomalies which the writer believes are caused by differences in the magnetic susceptibility of the basement rocks and possibly caused by intrusions into the basement metasediments of more basic igneous masses.

The gravity survey across Pennsylvania by NETTLETON [1941] gave little evidence of any major deformation of the basement. There were few or no gravity anomalies associated with major folding. This, of course, could be explained by assuming a very small or non-existent density contrast between the sediments and the basement rocks, if the basement were folded; or if not folded, by absence of density contrasts within the folded sediments.

Field work

All field stations were made along main traffic highways in order that elevations of the stations could be readily obtained. Along main highways the elevations were obtained from the Pennsylvania Highway Construction Profiles and are accurate to the nearest 0.1 ft. In some areas where elevations were not available from highway profiles, elevations were taken from U. S. Geological Survey stations and are probably accurate to the nearest foot.

Field work was carried out using a Frost gravity meter (No. 34-C), which has a scale constant of 0.086 milligal per scale division. It is possible to estimate the reading to ± 0.1 division, thus giving an ultimate precision to the measurements of better than ± 0.01 milligal. However, due to drift characteristics of the instrument and other inherent errors, such as reading errors, it is believed by the writer that the practical value for the precision of measurement of a single station is of the order of ± 0.05 milligal.

(A) Corrections of the gravity measurement--Corrections were made for (1) drift, (2) elevation, (3) "simple" terrain (Bouguer correction), (4) latitude, and (5) terrain.

(1) The drift of the instrument is reasonably small, amounting to about 0.15 milligal per hour. This was corrected by returning to the base station at approximately two-hour intervals and making a correction for instrument drift by interpolation.

(2) Elevation corrections were made using a constant of 0.09406 milligal per foot relative to an arbitrary base on the Pennsylvania State College Campus.

(3) "Simple" terrain or Bouguer correction was made using the value of 0.01285 σ milligal per foot, where σ is the density and was taken as 2.6. This value for the density seemed to be the best available for the Paleozoic rocks near State College though it is slightly lower than that used by NETTLETON [1941] in his work.

(4) Latitude corrections were made for all stations using the constant 1.3068 sin 2 ϕ milligal per mile, where ϕ is the latitude of the station. Stations were located on topographic maps and then corrections were made for them.

(5) The terrain correction was made for a radius of 21.826 ft. Stations were so located as to minimize the nearby terrain effect, that is, they were located at points where the terrain was not too rugged for a radius of approximately 200 ft. Where necessary, departures of the surface from flatness were estimated out to a radius of 175 ft; beyond that distance, topographic maps of the area were used in calculating terrain effects.

Principal source of error in the corrections would be caused by inaccuracies in the terrain corrections or to uncalculated effects from distances greater than 21,826 ft from the station. Calculated corrections were normally small, that is, usually under 0.5 milligal, although a few were of the order of four milligals. Considering the errors in terrain correction, it seems probable that the values of gravity of this survey are correct to better than one milligal. Thus for this survey, no anomalies were considered significant if they were not greater than one milligal and substantiated by more than one point.

Values for some stations were discarded when it was found impossible to locate the stations accurately on the map or where there was doubt as to the elevation.

(B) Reference base for gravity measurements--For the purposes of this survey, all measurements were referred to a base station established on the State College Campus and given an arbitrary value of zero.

Results of the field work

The results of the gravity survey are shown on the six traverse sheets, Figures 2, 3, 5, 6, 7, and 8. They will be discussed in order.

(A) Gravity traverse 1 extends from Amity Hall, north of Harrisburg, to Tioga, south of Lawrenceville on the Pennsylvania-New York boundary. This traverse follows U. S. Highways 11 and 15. The profile (Fig. 3) is projected upon a north-south line and compared with the corresponding structural section. A density of 2.6 is apparently quite satisfactory in calculating the simple terrain effect, as there is no apparent relationship between topography and the gravity profile.

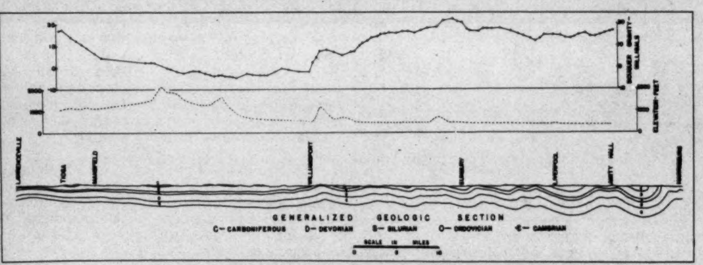

Fig. 2--Traverse 1, gravity profile from Amity Hall to Tioga (traverse and geologic section follow Highways 11 and 15)

Figure 2 is characterized by a very large gravity "plateau" extending from the southern end of the profile nearly to Williamsport. At Williamsport the gravity value decreases and remains relatively low between there and Mansfield. Near Mansfield the gravity value begins to increase at a rapid rate. This anomaly was later investigated by HOWELL and VOZOFF [1951].

There is no correlation between the folding of the sediments and the gravity anomalies. In some places gravity highs coincide with structural lows, notably near Sunbury where there is a five-milligal gravity high associated with a syncline. About five miles north of Liverpool there is a gravity low which coincides with a structural high. Several other such examples are evident. Near Williamsport, however, the value of gravity decreases very rapidly to a value of about minus two milligals. This coincides with the structural low which occurs at that point. This structural low, which lies just at the edge of the Allegheny plateau, will be seen to have a nearly constant value of gravity wherever crossed. The large gravity plateau north of Amity Hall will be referred to again when the results of the second traverse are discussed.

(B) Traverse 2 extends from Amity Hall westward beyond Snow Shoe, Pennsylvania, and follows U. S. Highways 53 and 322 (Fig. 3). This profile is relatively smooth, showing only two major anomalies. The largest and most important anomaly occurs near Mifflintown. In this area there is a change of about 18 milligals in a relatively short distance. There are no known structural conditions in this area which would indicate any cause for the anomaly; therefore, it is probably due to some change in the basement without surface expression. This explanation is also borne out by the magnetic anomaly which occurs there (Fig. 4), which shows excellent correlation with the gravity anomaly although displaced somewhat to the eastward. Since sediments, in general, are relatively non-magnetic, the magnetic anomaly is probably also associated with the basement. The area east of Mifflintown has a very high gravity value similar to that of the gravity plateau which was mentioned in the discussion of the southern half of traverse 1.

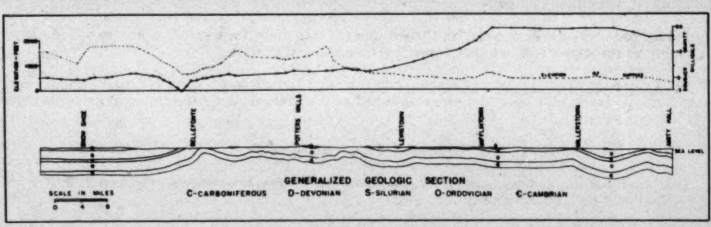

Fig. 3--Gravity profile from Snow Shoe to Amity Hall (traverse follows Highways 53 and 322)

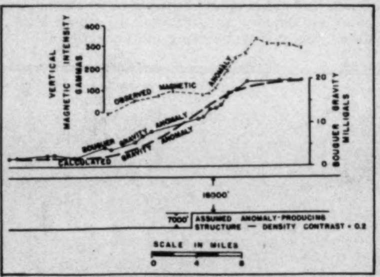

Fig. 4--Detail of gravity and magnetic anomalies of traverse 2 near Mifflintown, Pa., and calculated gravity effect for a step-block of infinite length

The appearance of the Mifflintown anomaly is very similar to that which would be produced by one edge of a raised block of the basement; or it may be due to an intrusion of the basement or sediments by a mass of greater density. If it is assumed that there is a step block on the igneous basement, one can calculate both the depth to the top of the upper block and the height which the upper block extends above the adjoining areas by means of the formula for the gravity effect of a semi-infinite slab of finite height even though no unique solution is possible.

Using a density contrast of 0.2 which is quite reasonable for a granite intruding into the sediments [NETTLETON, 1941, p. 275], approximate calculation gives a height of 7000 ft and a depth to the top of the intrusion or block of 16,000 ft, as suggested in Figure 4. There is a fair correlation between the shape of the observed gravity anomaly and one recalculated from theory, assuming the conditions shown. The discrepancies indicate that the block deviates from an ideal step as assumed in the calculations. The calculated fault depth and height are not unreasonable, being comparable with a geological estimate of the thickness of the sediments, that is, 15,000 to 20,000 ft according to a personal communication from F. M. Swartz; however, the geologic section shows a thickening, not a thinning, of the sediments to the east. If it were postulated that this upraised block is the edge of an intrusion of batholithic proportions, as indicated by the extent of the gravity plateau to the east and north (Fig. 2 and 3), that would help to explain the source of the thrust which formed the large northwestward salient in the Appalachian Front occurring in this portion of Pennsylvania (Fig. 1). Such an intrusion would probably have both an upward and a horizontal component of force, the horizontal force in this case would probably be toward the northwest.

There is one other condition which could cause this anomaly. This would be simply a change of composition in the basement complex, the portion to the east of Mifflintown being more basic and hence having a higher density and a greater magnetic susceptibility. The writer, however, favors the first explanation as given above.

The only other anomaly in traverse 2 worth mentioning is the one which occurs just west of Bellefonte. This is at the edge of the Allegheny Plateau and is undoubtedly associated with the structure there. This anomaly is narrower but has about the same gravity value as that near Williamsport.

(C) Gravity traverse 3 extends from Potters Mills to Penfield and follows U. S. Highways 53 and 322 (Fig. 5). This traverse shows mainly gradual changes. The low, near Port Matilda, lies approximately along the general trend of the edge of the Allegheny Front. Several sharp anomalies occur just east of Phillipsburg, but these are based on too few stations to be considered significant. This is in rather rugged country and the actual existence of the anomalies is doubtful, especially as there was some doubt as to the locations of the stations.

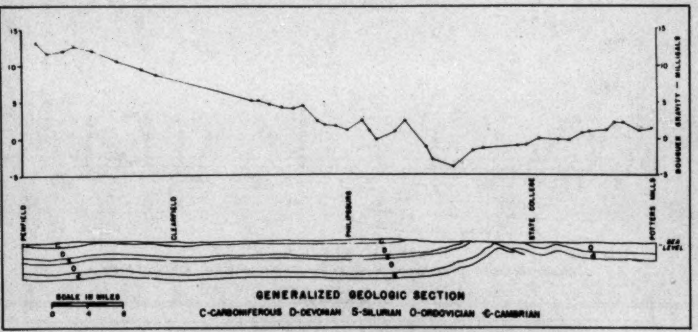

Fig. 5--Traverse 3, gravity profile from Penfield to Potters Mills (traverse and geologic section follow Highways 53 and 322)

In the area just south of Penfield there is a small gravity high between two lows which seems to correspond, neglecting the offset, with an extension of Chestnut Ridge to that area. Although the anomaly is quite small, it occurs in the same general relationship to the structural high as did the magnetic high when this area was covered by the Airborne Magnetic Survey [PIRSON and BACON, 1947].

(D) Gravity traverse 4 extends from Black Moshannon Lake to the Caledonia Pike 15 miles north of Clearfield (Fig. 6). This traverse was laid out so as to cross the Laurel Hill Anticline, which it does near the center of the profile, although it is not prominently shown in the geologic section. In this region there is a small gravity high but it is doubtful that it has any significance. The value of gravity increases to the westward on both this and traverse 3. It is possible that the basement is rising slightly toward the northwest, thus causing an increase in the relative gravity.

(E) Gravity traverse 5 follows U. S. Highways 22 and 422 from Huntingdon to Belsano, Pennsylvania (Fig. 7).

The western portion of the profile is very similar to that of traverses 2, 3, and 4. It shows a rather high gravity value to the westward and an area of lower gravity value near the Allegheny Front.

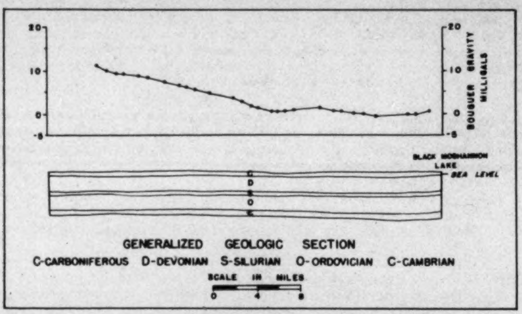

Fig. 6--Traverse 4, gravity profile along Caldonia Pike (traverse and geologic section follow Caledonia Pike southeast to Black Moshannon)

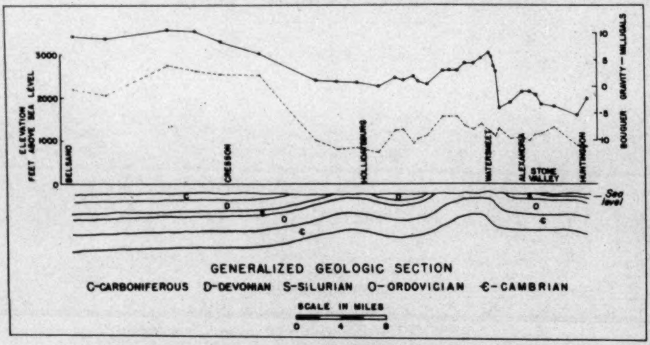

Fig. 7--Traverse 5, gravity profile from Huntingdon to Belsano (traverse and geologic section follow Highways 22 and 422)

The area of main interest is in the eastern portion of the profile from Huntingdon to Waterstreet. This shows two distinct anomalies; the first, near Alexandria, is about three miles wide and has a magnitude of about three milligals. The other, near Waterstreet, has a magnitude of about ten milligals. The Alexandria anomaly is probably associated with an intrusion or a change in the basement such as a dome. This latter idea was advanced by ZELLER [1941] as a possible cause for the structural thrust in the area. Zeller refers to a magnetic high in Stone Valley which corresponds in position to this gravity anomaly. It is probable that both are caused by an igneous mass, either on the basement floor or occurring as an intrusion. The anomaly at Waterstreet, however, seems to be more closely related to the structural conditions near the surface. The anomaly is very sharp, such as would be obtained by crossing a boundary between beds of different density or by passing over a fault. At this point the traverse crosses a boundary between relatively flat-lying rock of Silurian age to steeply dipping strata of Ordivician and Cambrian Age. There is a NE-SW fault in this area, for which the amount of throw is not known. It is believed by the writer that the anomaly at Waterstreet is caused by near surface structures.

(F) Traverse 6 crosses Stone Valley about ten miles north of Alexandria; the profile is projected upon a line striking N 46°W (Fig. 8). This traverse shows a broader gravity anomaly than that at Alexandria, but has the same general shape. It is believed that this one has an origin similar to the anomaly at Alexandria and closely related to it.

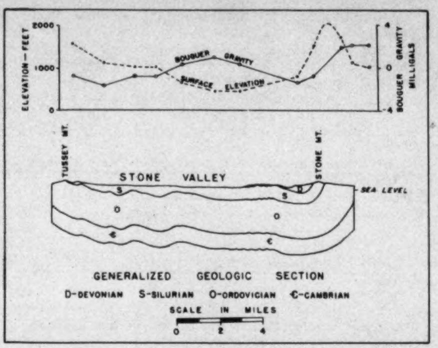

Fig. 8--Traverse 6, gravity profile across Stone Valley

Conclusions

(1) The results of the gravity survey of Pennsylvania indicate that there probably is a large intrusion or upthrust of the basement east of Mifflintown and south of Williamsport. The writer believes that this intrusion was probably responsible for the forces causing the northwestward structural salient of central Pennsylvania.

(2) The value of gravity along the front of the Allegheny Plateau is generally low and is apparently associated with the structural conditions there. The area of low gravity value becomes broader in the northern and southern traverses, its eastern edge surrounding the salient of mountain folds much like the bow waves near the prow of a ship.

(3) There is no distinct relationship between the gravity anomalies and major structural folding.

Acknowledgments

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GRAVITY TRAVERSE IN NORTHEASTERN PENNSYLVANIA

John C. Duecker

Abstract--A gravity traverse was made in northeastern Pennsylvania beginning near Millerton, in the Tioga area, extended south to Columbia Cross Roads, then east, following roads roughly parallel to the Pennsylvania border, to a point about a half-mile below Stockport Station on the Delaware River. The data taken along the traverse revealed a gravity profile with two significant features: a local anomaly of about 15 mg over a distance of eight miles near the town of Montrose, and a regional Bouguer gravity increase of 70 mg between Milan and Stockport, a distance of 65 miles.

Introduction--The traverse in this survey was chosen to supply gravitational information on northeastern Pennsylvania and to determine whether additional anomalies similar to those near Bradford [HAMMER, 1938] and Tioga [HOWELL and VOZOFF, 1952] occur. This was accomplished by a traverse beginning near Millerton, in the Tioga area surveyed by Vozoff, extending south to Columbia Cross Roads, then east to a point about a half-mile below Stockport Station on the Delaware River. This traverse is shown in Figure 1.

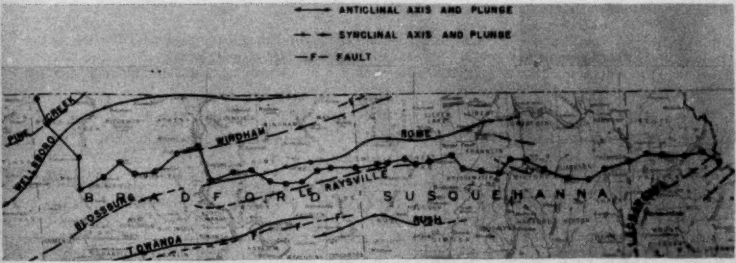

Fig. 1--Geologic structure in northeastern Pennsylvania and location of gravity traverse (one inch equals approximately 15 mi)

The area is a typical Appalachian Plateau surface. It consists of concordant ridges and numerous dissecting streams, which cut V-shaped valleys as they feed the Susquehanna and Delaware Rivers.

Geology--The stratigraphy of north-central Pennsylvania has been thoroughly studied [FETTKE, 1950]. The outcrops in Bradford County range from Middle Devonian to Pennsylvanian Age. The greatest part of the County is underlain by rocks of the Chemung formation. In Susquehanna and Wayne Counties the bedrock surface is almost wholly occupied by the Catskill formation. Glacial drift covers almost all of the three counties, particularly in Susquehanna and Wayne Counties where glacial dams and swamps are numerous.

The principal structural axes are shown in Figure 1 which is taken from CATHCART [1934]. In the Tioga gas field, west of the traverse, wells drilled have shown the intensity of folding to increase with depth and 200-ft displacement faulting to occur [TORREY and Others, 1932; FETTKE, 1940]. Similar subsurface structural variations may exist in northeastern Pennsylvania. No wells have penetrated to the crystalline basement, so it is not possible to determine the role it plays in determining the structure of the overlying sediments.

Although few data are available on the densities of the formations known to underlie the northeastern part of Pennsylvania, a value of 2.67 gr/cc is considered to be a good average value for all rocks in the Appalachian area [NETTLETON, 1941]. The general lack of gravity anomalies associated with structural features in this region also indicates an equality of densities in the Paleozoic sediments making up the mountains. Therefore, the large gravity anomalies found in northern Pennsylvania probably cannot be explained in terms of density contrasts among the sediments or between sediments and basement rocks.

A more probable cause of density contrasts in the subsurface rocks would be igneous intrusions. Peridotite intrusives [ρ = 3.2 gr/cc; BIRCH, 1942] such as those reported by HONESS and GRAEBER [1926] might provide a density contrast of 0.55 gr/cc, though Hess in a personal communication to B. F. Howell, Jr., in 1953 reports that the peridotites known to exist in this part of the United States are less dense than this. Diabase intrusions (ρ = 2.97 gr/cc), such as those that are common in the piedmont area, would be just as likely to be the cause of local anomalies as peridotite.

The presence of salt or lack of anhydrite such as occurs in small quantities in the Tioga gas field [FETTKE, 1950] could provide a density contrast; but they would have to occur in much larger quantities than have been observed in this part of the state to explain the gravity anomalies.

In this survey a density of 2.65 gr/cc was used in reducing the gravity data for the complete Bouguer corrections. This value was chosen to give reduced data in accord with that of BACON [1950] and HOWELL and VOZOFF [1952] whose surveys tie in with the west end of this survey.

Other gravity surveys made in the Appalachian region were reported by HERSEY [1944], HAMMER and HECK [1941], LONGWELL [1943], and WOOLLARD [1943ab and 1948ab; also a manuscript map in a personal communication in 1951].

Method--A base line was chosen to run as nearly parallel to the Pennsylvania border as the road system would permit and governed by the ability to secure elevation data along any stretch of road. The stations chosen averaged a little over two miles apart. In all, 40 stations were established in an east-west direction over a distance of about 85 miles.

Each station was located on U. S. Geological Survey topographic quadrangle maps, scale 1:62,500. The positions are believed to be accurate to two seconds of arc (about 200 ft).

Elevations were taken from U. S. Coast and Geodetic Survey and U. S. Geological Survey bench marks and from useful elevations indicated on the quadrangle sheets, such as road intersections and bridges. Only in the event that bench marks could not be found or were too far off the proposed traverse were the road intersections and bridges used for elevation reference. Most elevations taken from bench marks are good to a fraction of a foot; four taken from road intersections are known to the nearest foot; and one taken on a new bridge is known only to the nearest five feet. The greatest error introduced by this procedure is believed to be less than half a milligal.

For drift control the stations were occupied in a series of looping observations, described as the fifty per cent over-lap method [NETTLETON, 1940].

The gravimeter used throughout this survey was built by the Frost Gravity Meter Co. It is a mechanical, astatic instrument of the Galitzin type and consists principally of a horizontal beam pivoted at one end [WELCH, 1941].

Reduction of data--The reduction procedure used on these data is practically identical with that used on most present-day exploration surveys [NETTLETON, 1940]. It consisted of five corrections: drift correction, latitude correction, free-air correction, simple Bouguer correction, and topographic and terrain corrections. The reduced data of this survey are shown in Figure 2a.

Interpretation--The complete Bouguer anomaly is shown in Figure 2a. This profile is smoothed by inspection using an engineer's flexible rule. This smoothed curve is hereafter referred to as the regional anomaly. It is then subtracted from the complete Bouguer anomaly. The difference, shown in Figure 2b, is called the residual anomaly.

The outstanding feature of the residual anomaly is the variation in the vicinity of Montrose. The data concerning this anomaly are too few to justify drawing smooth curves through the known points and constructing geometrically regular forms which might approach classical textbook anomalies. Another difficulty is that no knowledge of the shape of the anomaly transverse to the traverse is available.

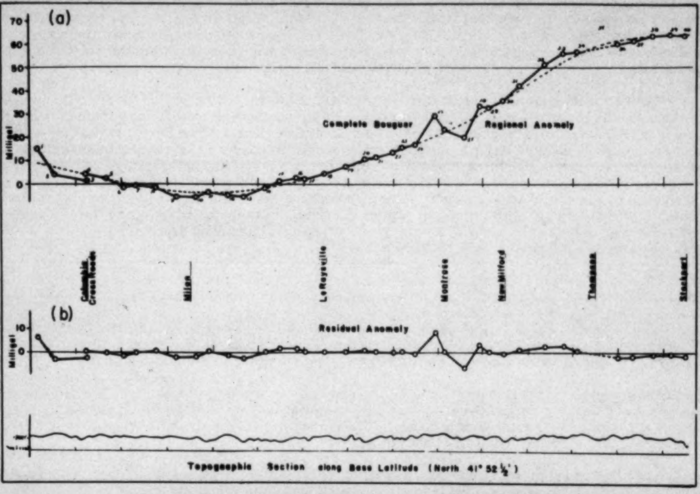

Fig. 2--Bouguer gravity anomalies and topographic profile

Two hypotheses can be suggested which would account for the observed variation of gravity. One is that it is caused by faulting of a shallow layer such as a salt bed or of a dense igneous sill in the manner of a graben. Faults of several hundred feet displacement occur and folding becomes more intensified with depth in the Tioga area [FETTKE, 1940], and it is possible that the subsurface structure in this area is similar. It is, however, doubtful that the sediments have sufficient density contrast to produce gravity anomalies where faulting occurs [NETTLETON, 1941; HAMMER and HECK, 1941]. A deformed igneous sill, or a buried flow, is the only variation of this hypothesis which seems reasonable.

The other hypothesis is that irregular intrusions of either peridotite or diabase such as those which occur in New Jersey and in southeast Pennsylvania also occur beneath Montrose. An anomaly of almost equal magnitude north of Tioga was investigated and interpreted by HOWELL and VOZOFF [1952]. They show that the greater part of this anomaly could be accounted for by presence of a buried intrusion of diabase or peridotite. A similar assumption could account for the anomaly found by this survey. However, the low between the two highs cannot be explained by this hypothesis without lowering the regional base line throughout the whole area of this anomaly.

The regional anomaly fits in very well with the Bouguer gravity anomaly maps of the Eastern Seaboard of the United States, compiled by NETTLETON [1941] and WOOLLARD [1943b and 1949]. On Woollard's 1949 map a gravity high extends from somewhere below Susquehanna County, through Wayne County and into New York State along a northeasterly trend. The left flank of this high is not complete but there is sufficient information shown to suggest that the gravity decreases 40 to 60 mg between Stockport and the west border of Susquehanna County. The regional anomaly revealed by this survey (Fig. 2a) decreases 55 mg over the same distance, and is further decreased by another 15 mg near Milan in the center of Bradford County.

The regional anomaly reported in this survey appears to be a part of and an extension of the areal anomaly reported in the northeast corner of Pennsylvania by Woollard and Nettleton. NETTLETON [1941] believed that this high is a continuation of the Laurel Ridge high found at the junction of the West Virginia, Maryland, and Pennsylvania borders. The data of this survey support this conclusion by tracing the anomaly further west. SWICK [1940] reports that a further continuation is suggested in the northeast corner of Tennessee. Since these gravity features are closely parallel with the Appalachian Mountains they must be closely related to the regional tectonics of the area.

Nettleton proposes that the principal causes of the gravity anomalies in the Appalachian region are in density contrasts very deep within the Earth's crust. Woollard has several suggestions, one being that late Paleozoic compressional forces fractured the crust and over-thrust the eastern member, so that the over-ridden member was forced down into the substratum, thus providing a low density contrast in the rocks through southeastern Pennsylvania.

SWARTZ [1948] states that crustal shortening and thickening can plausibly explain the present-day Appalachian gravity features. The shortening, at the time of the Appalachian folding, occurred in the deep basement by widely distributed failure involving metamorphic recrystallization. The sedimentary cover adapted itself to the shortening within the basement by buckling and faulting. Minor plastic shortening to the west would be reflected in small amplitude flexures in the sedimentary cover. This buckling of the basement rocks may explain the regional variations in gravity; but because of the lack of strong density contrasts between the sediments and underlying crystalline rocks, or within the sediments, it cannot explain the more local anomalies such as the one at Montrose. The presence of such anomalies suggests that igneous intrusions are more prevalent in this part of Pennsylvania than has been realized before.

Isostatic correction apparently does not remove the regional anomaly seen in this survey. A comparison with the isostatic anomaly map of Pennsylvania prepared by NETTLETON [1941] reveals the same regional gravity increase in the northeast corner.

This survey has, therefore, extended the area in Pennsylvania for which the regional gravity is known, and has revealed another small local anomaly worthy of more detailed study.

Acknowledgments--The writer would like to express his appreciation to B. F. Howell, Jr., of the Division of Geophysics and Geochemistry at Pennsylvania State College, who gave very generously of his time and experience in conducting this survey and in preparing the paper, which is a condensation of the master's thesis of the writer.

In addition the writer would like to thank F. M. Swartz of the Division of Geology at Pennsylvania State College for advice and guidance on the geology of the region.

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NOTES ON THE ATMOSPHERIC REFRACTIVE INDEX IN CANADA FROM AIRCRAFT METEOROLOGICAL SOUNDINGS

Arthur S. G. Grant

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Abstract--Calculations of the atmospheric refractive index for radio waves were made from aircraft soundings over a large area of northern Canada in connection with the 1952 season of the shoran survey. A comparison is made between the results and the NACA 60 pct relative humidity standard atmosphere.

Introduction--An atmospheric sounding is made on each line measured by shoran. This is done to obtain data required for the evaluation of the aircraft elevation, and for the reduction of the shoran "distance" to map distance. The results of 151 soundings made in the summer of 1952 indicate that average conditions were very close to those in the NACA standard atmosphere with relative humidity of 60 pct.

Sounding technique--Although this is adequately described elsewhere [NORDMAN, 1950], it will be reviewed briefly. The procedure consists of a helical flight between the lowest safe-flying elevation and the operating elevation, normally 15,000 to 20,000 ft above mean sea level. At thousand-foot intervals of pressure altitude, the aircraft levels off and maintains steady indicated airspeed long enough to allow the instruments to attain equilibrium. The wet and dry bulb temperatures, indicated airspeed, and pressure altitude are then noted and recorded. The measurements are required to be taken within a vertical cylinder of five miles radius, centered over the mid-point of the line being surveyed. In clear weather over flat country, the soundings are taken to within a few hundred feet of ground level. When overcast conditions exist in the lower levels, the minimum indicated altimeter height may be raised to 2000 ft above the highest known elevation in the surrounding country. Of the 151 soundings taken, 124 included the 2000-ft pressure altitude surface and 20 the 20,000-ft surface. The upper limit of the sounding depended upon the length of the shoran line being measured and upon radio propagation conditions. The operating height was chosen generally as that at which the strongest return signals from the ground beacon stations were observed. The ceiling of the aircraft used was about 22,000 ft.

Most of the soundings were taken during daylight hours, an estimated 95 pct being between 09h 00m and 17h 00m local standard time. The season lasted from June 23 to the end of September, 1952. The first area of operation extended from Great Slave Lake northward to the Coronation Gulf, thence eastward across the District of Keewatin to the southwestern tip of Foxe Peninsula and northwestern Ungava. This portion was completed by August 23. From September 4-30, operations were carried out in eastern Quebec and southern Labrador.

The soundings were taken, insofar as possible, without regard to weather conditions at the line. There are several examples of soundings taken under saturated conditions throughout all levels. At least three were taken through active frontal surfaces, and one was made in the center of a deep occluded depression. However, most were characterized by cloud-free conditions over 85 pct (estimated) of the sounding. On only one occasion were attempts at shoran measurements prevented by heavy icing, which limited the climb to 13,000 ft. On one other occasion, the aircraft was forced to return to the base on account of severe icing. Operations were delayed for one and one-half days in early July due to poor surface weather at the base of operations. Thus it is felt that the complete set of soundings is representative of average daytime conditions in the area concerned for the summer of 1952.

Computation of index of refraction--Because of the high speed of the aircraft, corrections to the observed temperatures were required to yield true free-air temperatures. This was done in the usual fashion [ANONYMOUS, 1945], the dynamic heating coefficient for the installation having been determined previously from experiment. Frequently, in cloud, and possibly occasionally in cloud-free flight, straight application of the wet and dry dynamic heating corrections produced apparent supersaturated free-air conditions. Under such circumstances the air was assumed saturated at the corrected wet-bulb temperature.

The refractive index was computed from the following relation

$$(n - 1) \times 10^6 = (76.43/T)\,[p - 0.12e + 4929\,e/T] \quad \ldots\ldots (1)$$

where p is the total pressure in millibars, e the partial pressure of water vapor in mb, and T the absolute temperature. In practice the small term in e was neglected and a graphical method used whereby n - 1 was obtained directly from the observed pressure altitude and corrected dry- and wet-bulb temperatures.

Results--From the shoran work sheets the value of the refractive index at each even thousand-foot level of pressure altitude was abstracted. The seasonal average and the standard deviation for each such level were calculated. The results are shown in Table 1. To the resulting average figures a smooth curve was fitted by the method of grouping [GUEST, 1952]. The fitted curve obtained was

Table 1--Results of computations

Pressure altitude	Seasonal mean refractive index $(n - 1)$	Standard deviation	Number of observations	Smoothed mean $(\bar{n} - 1)$	NACA atmospheric 60 pct rel. hum. $(n_s - 1)$
ft					
2000	293.4×10^{-6}	9.5×10^{-6}	124	294.0×10^{-6}	294.2×10^{-6}
4000	273.0×10^{-6}	7.9×10^{-6}	149	272.4×10^{-6}	272.8×10^{-6}
6000	252.6×10^{-6}	6.5×10^{-6}	151	252.0×10^{-6}	252.7×10^{-6}
8000	232.8×10^{-6}	5.3×10^{-6}	151	233.0×10^{-6}	234.0×10^{-6}
10000	214.5×10^{-6}	4.7×10^{-6}	146	215.3×10^{-6}	216.6×10^{-6}
12000	198.4×10^{-6}	4.0×10^{-6}	139	198.9×10^{-6}	200.6×10^{-6}
14000	183.9×10^{-6}	3.1×10^{-6}	126	183.9×10^{-6}	186.0×10^{-6}
16000	170.3×10^{-6}	2.6×10^{-6}	85	170.1×10^{-6}	172.7×10^{-6}
18000	158.3×10^{-6}	1.4×10^{-6}	46	157.7×10^{-6}	160.8×10^{-6}
20000	146.6×10^{-6}	1.7×10^{-6}	20	146.6×10^{-6}	150.3×10^{-6}

$$(\bar{n} - 1) \times 10^6 = 317.0 - 11.82h + 0.165h^2 \quad \ldots\ldots (2)$$

where h is the height in thousands of feet (strictly the pressure altitude), and $\bar{n}$ is the smoothed mean refractive index at height h. The smoothed standard deviation σ is given by

$$\sigma \times 10^6 = 10.9 - 0.795h + 0.0137h^2 \quad \ldots\ldots (3)$$

The NACA standard atmosphere with 60 pct relative humidity is sometimes taken as a standard atmosphere in radio wave propagation studies [COOPER, 1947]. In this atmosphere the relation between refractive index and height is given by

$$(n_s - 1) \times 10^6 = 317.0 - 11.74h + 0.170h^2 \quad \ldots\ldots (4)$$

In the diagrams presented below, differences between the observed values and the standard values determined from (4) are plotted. This method of plotting is used to show more readily the differences between the various soundings. Four sample soundings are shown, demonstrating the magnitude of the variations encountered. Examples 1 and 2 are of interest in that they illustrate the advance of an active front across the line being surveyed. Figure 1 shows soundings taken 24 hours apart at the same location. The first sounding was made entirely in cloud, with rain falling to the surface from above the 3000-ft level. The top of the frontal inversion appears at 4000 ft. On the following day the frontal surface had risen to 10,000 ft. On this date there was no cloud or weather reported at the sounding site, the area of activity having moved southward with the surface position of the cold front.

The corresponding plots of refractive index are shown in Figure 2. In spite of the great difference in weather conditions existing during the two days the difference in calculated map distance was about 17 ft which is an average spread between means of measurements of distance by shoran made on separate days [ROSS, 1951]. (The 1000- and 2000-ft points of curve 1 and the 1000-ft point of curve 2 of Figure 2 were interpolated from surface meteorological data.)

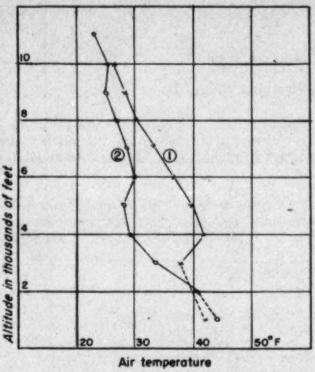

Fig. 1--Temperature soundings taken 24 hours apart showing cooling due to frontal passage

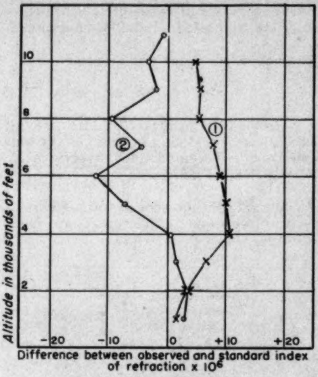

Fig. 2--Relationship of refractive index to height

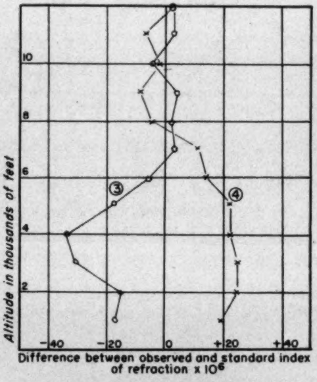

Fig. 3--Examples of high and low refractive index in low levels

Examples 3 and 4 (Fig. 3) show respectively large negative and large positive deviations from the mean curves of refractive index versus height. It will have been noted that deviations from the mean are small in the upper levels. This is a characteristic of all the soundings and is, of course, due to the small possible range of the water vapor pressures in the upper levels of the atmosphere.

Acknowledgment--I wish to acknowledge the assistance of John Kennedy in the computation of the refractive indices.

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DISCUSSION OF

"EXPERIMENTS WITH WINDSHIELDS FOR PRECIPITATION GAGES"

by C. C. WARNICK

[Trans., v. 34, pp. 379-388, 1953]

Samuel B. Cross (Suffolk County Highway Department, Port Jefferson, N. Y.)--As a cooperative observer for the U. S. Weather Bureau, the Suffolk County Highway Department has operated a Friez dual traverse recording rain gage at Cutchogue, New York, since May, 1940. From May, 1940, to August, 1952, the gage was equipped with a standard Alter flexible windshield and a collecting tube 11.314 inches in diameter with 15-inch vertical sides on the top of the standard collector. This tube had an area exactly twice the size of a standard eight-inch collector, and was used to double the scale on the chart. The top of the windshield was placed level with the top of the collecting tube.

In February, 1948, when the windshield was repainted and the connecting restraining chains were replaced, the baffles were inadvertently replaced on the circular rods inside out; that is, the top of the baffles curved inwardly instead of outwardly.

When this was discovered early in 1952, another Friez dual traverse recording rain gage was established 500 ft northeast of the original gage in order to determine the relative catch in the gages. Table 6 shows that with the windshield reversed, and using the large collecting tube, the catch was higher than normal. On July 31, 1952, the large collecting tube was removed and the windshield was installed properly. Table 6 also shows the records for the three months following the change.

Table 6--Comparative precipitation measurements during 1952

Month	Original gage	Unshielded gage	Ratio
	inch	inch	pct
April	4.66	2.56	182
May	7.88	4.13	191
June	4.71	2.89	163
July	1.12	0.82	137
Total	18.37	10.40	177
August	9.97[a]	9.83	101
September	1.37	1.45	94
October	0.68	0.68	100
Total	12.02	11.96	100.5

[a] Shield properly installed from August onward.

The double-mass analysis for testing the consistency of meteorological records, first described by MERRIAM [1937] and later by KOHLER [1949], was computed for the records at Cutchogue.

Figure 13 shows the location of the base stations available. The Bridgehampton gage had been relocated during this period so it could not be used as a base. Figure 14 shows that using the large collector with the windshield gave a slope of 0.57, and when the windshield was reversed the slope increased to 0.68. For the past year, with the regular eight-inch collector and the properly installed windshield, the slope was 0.48. The calibration of the gage was checked periodically so that the variations in the catch cannot be attributed to changes in calibration. It would appear that Warnick was correct in stating that shields play an important part in the amount of precipitation caught and that the distance from the shield to the edge of the collector varies the amount of the

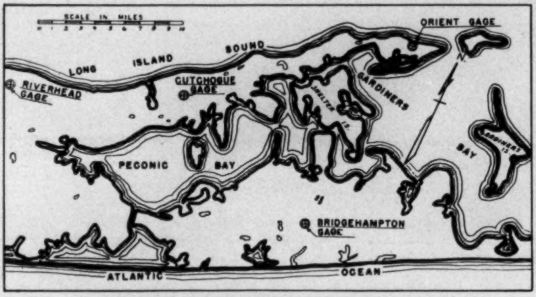
SCALE IN MILES
ORIENT GAGE
LONG ISLAND SOUND
RIVERHEAD GAGE
CUTCHOGUE GAGE
GARDINERS BAY
SHELTER IS.
GARDINERS IS.
PECONIC BAY
BRIDGEHAMPTON GAGE
ATLANTIC OCEAN
N

Fig. 13--Map showing the location of the rain gages eastern Suffolk County, Long Island, N. Y.

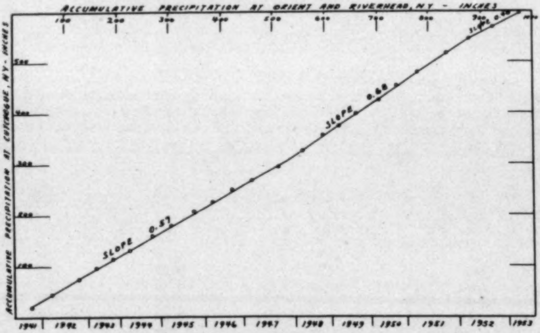

Fig. 14--Accumulative precipitation in six-month periods, February to July and August to January

precipitation caught. This was also an excellent example of the use of the double-mass analysis for making adjustments to the precipitation records.

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C. C. Warnick (Engineering Experiment Station, University of Idaho, Moscow, Ida., Author's closure)--The comments by Cross are interesting and, though based on records of a very limited length, do tend to bear out data found in the writer's investigation. Recent results from the wind tunnel and field station experiments show that bending the baffle aids in stabilizing air currents flowing over the top of a precipitation gage. Larger diameter shields than the Alter shield appear to be advantageous; however, in very gusty winds care must be taken to be sure the shields are strong enough.

The larger the orifice and storage container, the greater the need for shielding. If measurements of precipitation in the form of snow are to be made in regions where winds greater than ten miles per hour are frequent, there is definite need for wind shields, and the designs studied by the writer have shown considerably greater consistency than any previously used.

DISCUSSION OF

"THE CELERITY OF VERY LARGE FLOOD WAVES IN THE ARKANSAS BASIN"

by CHARLES D. HOPKINS, JR.

[Trans., v. 34, pp. 594-596, 1953]

G. G. Commons (2601 Bridle Path, Austin 3, Texas)--The flattening of flood crests as a flood wave travels downstream is usually ascribed to valley storage, and in so doing there is neglected or overlooked a phenomenon which is due primarily to the shape of the flood wave. Figure 2 shows an instantaneous profile of a flood wave in a channel, which, for sake of simplicity, is assumed to have a uniform slope. At this particular instant, the crest of the flood is at point C. The line A-B is parallel to and at a depth y above the stream bed, thus representing the water surface profile for uniform flow for some particular quantity Q. At this instant, this depth y is the depth at an upstream point U and at a downstream point D. At the upstream point the flood wave is falling; at the downstream point it is rising.

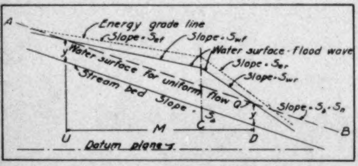

Fig. 2--Instantaneous profile of a flood wave in a channel

Subscripts are used to denote conditions or locations of depth y, slope S, velocity V, and quantity Q, as follows:

n	Normal conditions, uniform flow at depth y_n and quantity Q_n
w	Water surface
e	Energy profile or grade line
f	Falling side of flood wave
r	Rising side of flood wave
u	Conditions at upstream point U
d	Conditions at downstream point D

From the geometry of Figure 2, conditions at points U and D, separated by the distance M, are readily apparent, as follows:

$$\begin{array}{lll} y_u = y_n & \qquad & y_d = y_n \\ S_{wf} < S_n & & S_{wr} > S_n \\ S_{ef} < S_n & & S_{er} > S_n \\ V_u < V_n & & V_d > V_n \\ Q_u < Q_n & & Q_d > Q_n \end{array}$$

At any later time, owing to the greater velocity at the downstream point, the distance between the points having the same depth y must be greater. In the absence of tributary inflow between the points U and D, the crest must necessarily flatten as it travels downstream, in order to compensate for this "pulling apart" of the points U and D. This phenomenon is quite noticeable even in lined irrigation canals, where valley storage is at a minimum. In a natural stream where valley storage is of much more importance, this flattening of the flood crest is much more pronounced. Should the crest at a downstream station be equal to or greater than at an upstream station, it is direct indication of tributary inflow. Also, and this point needs no demonstration, the presence of a larger volume, in acre-feet or cfs-days, at the lower station is in itself proof of tributary inflow in the reach between the stations.

Tributary inflow may be in phase with the flood wave, so that the effect is to increase the peak flow at the downstream station, or it may be of such amounts and at such times as to distort the apparent time of travel, so that, in extreme cases, the crest of a flood may have an apparent travel time equal to express train speed. In the flood of June 14, 1935, on the Llano River near Junction, Texas, the crest appeared at noon, while the crest occurred at Castell, about 50 airline miles downstream, at 13h 00m. A secondary crest at Castell, at 23h 00m, is much more representative of the true travel time between the two stations.

The apparent travel time of a flood crest between two stations is equal to the true time only when (1) the tributary inflow between the stations is so small as to be negligible, or (2) the tributary inflow is known to be in phase with the flood crest in the main stream. Should these conditions not be fulfilled, the apparent travel time becomes meaningless.

Table 4 gives the flood crest and volume data for the Arkansas River for the reach Van Buren to Dardanelle and for the same floods given in the author's Table 1, volumes being computed from data given in U. S. G. S. Water-Supply Papers. Of these 12 floods, only the last two had volumes at Dardanelle less than at Van Buren. Of the remaining ten, all had larger volumes, and five had higher crests at Dardanelle, thus plainly showing the presence of tributary inflow in the reach. The wide variation in the apparent time of crest travel must be due to this tributary inflow unless it can be shown that the tributary inflow is in phase with the main stream crest.

Table 4--Flood crests and volumes, Arkansas River, Van Buren to Dardanelle

Date of Van Buren crest	Crest flows		Flood volumes				Remarks
	Van Buren	Dardanelle	Van Buren		Dardanelle		
			Period	Volume	Period	Volume	
	cfs	cfs		cfs-days		cfs-days	
Apr. 22, 1941	301,000	294,000	Apr. 16 to Apr. 30	2,212,700	Apr. 17 to May 1	2,277,000	
Oct. 18, 1941	200,000	220,000	Oct. 15 to Oct. 23	1,250,500	Oct. 16 to Oct. 24	1,324,200	Dardanelle crest higher
Oct. 28, 1941	202,000	207,000	Oct. 24 to Oct. 30	1,122,800	Oct. 25 to Oct. 31[a]	1,148,900	Dardanelle crest higher
Nov. 3, 1941	485,000	433,000	Oct. 31 to Nov. 10	3,598,000	Oct. 31 to Nov. 11[b]	3,675,800	
May 12, 1943	850,000	684,000	May 10 to May 18	3,956,000	May 11 to May 19	4,301,000	
May 23, 1943	750,000	680,000	May 19 to June 2	5,510,000	May 20 to June 3	5,587,000	
Apr. 18, 1945	650,000	584,000	Apr. 14 to Apr. 24	4,397,000	Apr. 15 to Apr. 25	4,645,000	
May 14, 1947	144,000	146,000	May 13 to May 16	409,700	May 14 to May 17	478,000	Dardanelle crest higher
May 25, 1947	185,000	194,000	May 23 to May 30	1,146,000	May 24 to May 31	1,264,000	Dardanelle crest higher
June 3, 1947	154,000	162,000	June 1 to June 6	654,000	June 2 to June 7	750,600	Dardanelle crest higher
June 26, 1948	330,000	299,000	June 23 to July 6	3,018,000	June 24 to July 7	2,924,200	
May 22, 1949	323,000	302,000	May 19 to June 2	3,007,000	May 20 to June 3	2,998,000	

[a] Three-fourths of October 31 flow assigned to this flood.

[b] One-fourth of October 31 flow assigned to this flood.

Table 5 gives the flood crest and volume data for the Verdigris River for the reach Independence to Lenapah and for the floods as given in the author's Table 2. Of the 12 floods listed, volume data are available for the first 11, and all of these show larger volumes at Lenapah than at Independence. In addition, three of the floods have higher crest flows at the downstream station. The presence of tributary inflow is very apparent, and in amounts to distort the travel time in most cases.

No attempt is made to analyze the data given in Table 3 for the Neosho River from Iola to Parsons, since no data are available to determine the crest flow or flood volume at the downstream station. However, the wide variation in the apparent time of travel justifies the surmise that tributary inflow plays a very important part.

It is probable that a study of travel times, using those floods where tributary inflow does not materially affect the apparent travel time, would show that, in general, the travel time decreases

Table 5--Flood crests and volumes, Verdigris River, Independence to Lenapah

Date of Independence crest	Crest flows		Flood volumes				Remarks
	Independence	Lenapah	Independence		Lenapah		
			Period	Volume	Period	Volume	
	cfs	cfs		cfs-days		cfs-days	
June 4, 1941	25,700	24,700	June 1 to June 6	89,790	June 2 to June 7	102,260	
Sep. 6, 1942	24,970	24,200	Sep. 4 to Sep. 10	98,880	Sep. 5 to Sep. 11	103,200	
May 7, 1943	21,700	28,000	May 6 to May 14	109,311	May 7 to May 15	190,150	Lenapah crest higher
June 5, 1943	20,000	21,000	June 3 to June 7	38,740	June 4 to June 8	51,250	Lenapah crest higher
Mar. 20, 1944	31,800	29,100	Mar. 15 to Mar. 26	152,890	Mar. 16 to Mar. 27	163,630	Date incorrectly given in Table 2 as May 20, 1944
Apr. 24, 1944	56,000	53,500	Apr. 21 to Apr. 29	188,550	Apr. 22 to Apr. 30	245,560	
Sep. 28, 1944	19,400	24,000	Sep. 26 to Sep. 30	29,262	Sep. 27 to Oct. 1	53,180	Lenapah crest higher
Dec. 6, 1944	26,040	24,500	Dec. 4 to Dec. 10	94,500	Dec. 5 to Dec. 11	112,700	
Mar. 26, 1945	27,800	25,400	Mar. 24 to Apr. 2	129,990	Mar. 25 to Apr. 3	136,400	
Apr. 17, 1945	112,000	91,000	Apr. 12 to Apr. 23	290,690	Apr. 13 to Apr. 24	345,300	
July 2, 1945	22,830	21,600	June 30 to July 5	56,420	July 1 to July 6	58,550	
July 1, 1951	100,000[a]	90,000[a]	(data not yet available)				

[a] Estimated, see Table 2.

as the crest becomes higher. Many factors, however, are concerned in this problem, some readily soluble; others difficult, or even impossible of solution.

Ralph E. King (Mississippi River Commission, Vicksburg, Miss.)--The statement by Hopkins that very large flood waves on certain rivers in the Arkansas Basin travel considerably more rapidly than flood waves of moderate size is in direct opposition to the general concept of flood crest travel. Since the occurrence of such flood waves on any particular river is very infrequent, the hydrological data pertaining to these floods are quite meager and unfortunately, because of the conditions existing at the time, often unreliable. Consequently, as more data become available, apparent hydrologic phenomena as indicated by the records for an individual flood can be confirmed or, if later data indicate the original records to be erroneous, discounted.

An inspection of the graph for the Van Buren to Dardanelle reach of the Arkansas River as shown in Figure 1 of the paper by Hopkins shows that the apparent increase in the rate of crest travel for very large flood waves is predicated primarily on the data shown for the crest of May 12, 1943 (maximum of record), and secondarily on the data shown for the November 3, 1941, crest.

Because the exact time of occurrence of a crest stage at any gage is often unknown, the hydrologist is, of necessity, forced to estimate the time required for crest travel between two gages from such records as are available. The determination of the time of occurrence of the peak discharge of a flood on a large stream is much more difficult because the decrease in slope which occurs as the crest stage approaches invariably causes the peak flow to occur prior to the recording of the crest stage. For this reason, and also because the damage caused by a flood is more nearly related to the maximum height of the flood waters than it is to the maximum volume, this discussion will be confined to crest travel as indicated by stages rather than by volume of flow as used by Hopkins. (Hopkins used crest data in terms of stage in the data shown for the Neosho River, although discharges are available at both the Iola and Parsons stations.)

The travel times of the 12 crests shown in Table 1 of the original paper were estimated by the writer and are compared in Table 6 with the corresponding travel times as estimated by Hopkins.

Table 6--Crest data, Arkansas River, Van Buren to Dardanelle (in terms of stage)

Date of Van Buren crest	Recorded crest stage at Van Buren	Estimated travel time	
		By Hopkins	By King
	ft	hr	hr
Apr. 22, 1941	30.8	36	38
Oct. 18, 1941	26.4	36	24
Oct. 28, 1941	26.5	30	27
Nov. 3, 1941	35.8	60	52
May 12, 1943	38.0	35	54
May 23, 1943	36.8	48	43
Apr. 18, 1945[a]	38.1	48	58
May 14, 1947	21.4	23	24
May 25, 1947	25.0	21	19
June 3, 1947	23.5	24	22
June 26, 1948	30.6	27	36
May 22, 1949	29.0	24	30

[a] Crest stage occurred on April 17, 1945.

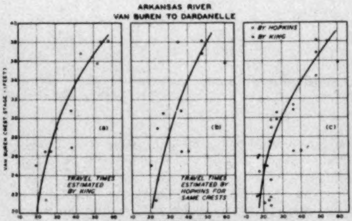

Fig. 3--Relationship of crest travel time to crest stage

The relationship of crest travel time to crest stage as estimated by the writer for the crests shown in Table 6 is presented graphically in Figure 3a. For comparative purposes the relationship defined by the travel times presented by Hopkins is shown on Figure 3b. It is readily apparent that the two relationships are quite similar and that there is no indication of an increase in the velocity of crest travel for the very high floods. Although the data estimated by the writer happen to plot more nearly in line than do the data estimated by Hopkins, no opinion is advanced as to which are the more accurate and, with the exception of the May 12, 1943, crest, the writer is willing to accept the crest travel times determined by Hopkins.

The crest travel time shown by Hopkins for the May 12, 1943, crest was 35 hours, while the writer's estimate for the same crest was 54 hours. The longer travel time is believed to be substantiated by an inspection of the U. S. Weather Bureau stage records for the Van Buren, Ozark, and Dardanelle gaging stations. The crest stage at Dardanelle is shown as having occurred at 07h 00m on May 14, 1943, while the crest stage at Ozark, which is located approximately 57 miles upstream from Dardanelle and approximately 44 miles downstream from Van Buren, is shown as having occurred at 19h 00m on May 14, 1943, 12 hours after the supposed crest stage at Dardanelle. Obviously, since inflow from the intermediate area was negligible, one of these crest times is in error. If the time of crest occurrence at Ozark is assumed to be correct, the crest would have reached Dardanelle at a time more than 12 hours subsequent to the published time of occurrence since allowance must be made for the time required for the crest to travel the 57 miles between Ozark and Dardanelle.

The assumption that the time of crest occurrence at Dardanelle is the one in error is believed to be substantiated by the estimated travel times for the April 18, 1945, November 3, 1941, and May 23, 1943, crests which reached stages higher or nearly as high as the May 12, 1943, crest. Records published by the U. S. Geological Survey show the crest discharge of the May 12, 1943 flood as having been 850,000 cfs and that of the April 18, 1945, flood as having been only 650,000 cfs although the latter flood crested at a slightly higher stage. This seems to leave the published flows for these floods subject to question.

To lend further weight to the arguments advanced herein, the writer estimated the travel times for 16 additional crests which occurred during the 1935-1949 period. These crest stages at Van Buren and their estimated times of travel in terms of stage are shown in Table 7.

Table 7--Additional crest data, Arkansas River, Van Buren to Dardanelle (in terms of stage)

Date of Van Buren crest	Recorded crest stage	Estimated travel time
	ft	hr
June 17, 1935	34.3	48
Jan. 17, 1937	22.0	18
Feb. 2, 1937	21.1	21
June 14, 1937	21.7	24
June 19, 1937	20.8	24
June 13, 1941	27.5	24
Oct. 9, 1941	26.0	18
Apr. 12, 1942	27.8	27
Apr. 23, 1942	24.3	18
Apr. 30, 1942	31.3	36
Mar. 4, 1945	23.9	10
Mar. 21, 1945	29.8	24
Apr. 13, 1947	23.8	20
Apr. 27, 1947	24.9	22
Apr. 30, 1947	25.8	17
July 25, 1948	21.9	17

The graphical relationship between crest stage and travel time as indicated by a summation of the data presented in Tables 6 and 7 is shown on Figure 3c. Except for the May 12, 1943, crest, the travel times used for the 12 crests shown in Table 6 were those determined by Hopkins. The use of the travel times estimated by the writer would have very little effect on the relationship.

The writer has not had sufficient time for a study of the data presented by Hopkins for the Verdigris and Neosho Rivers, but does feel that further detailed analysis should be made of all available data before the acceptance of this apparent phenomenon as being correct for either stream.

Charles D. Hopkins, Jr. (Tulsa River Forecast Center, U. S. Weather Bureau, Tulsa, Okla., Author's closure)--The author explicitly stated the presence of tributary inflow, not only during the periods of the flood waves, but also on downstream crests. Quoting from the paper, "Some indication of the effects of inflow occurring within the reach is included in each case and crest travel times are included only for those cases where this local runoff can be assumed to have a negligible effect on the time of occurrence of the downstream crest." It was not feasible to show all the analyses of various rises considered in this study, many of which were eliminated for one reason or another. In downstream reaches, crest travel times are readily derivable for many rises and afford a very useful tool for inferring the nature of the storage relationships of a reach, as well as being valuable in themselves.

The reasoning of Commons on the effect of tributary inflow on the time of a main stem crest seems incomplete. He assumes that, for the crest travel time to be unaffected, the tributary inflow must be negligible or exactly in phase with the main stem flood wave. Evidently, from the computations submitted in Tables 4 and 5, it was tacitly assumed that the tributary inflow must be negligible throughout the entire period of the flood wave for crest travel time to be unaffected. The unconsidered case is that when the tributary inflow wave is distinctly out of phase with the main stem flood wave.

It is, of course, true that the presence of tributary inflow at any time effects the passage of a flood crest through a reach by (1) satisfying storage demands on the rising side of the flood wave, and (2) throwing the main stem flow into a range of flow where storage may be quite different than in the original range. These effects are, however, so small with the usual proportions of volumes of local and main stem flow that they can be and usually are neglected. Therefore, it would be generally agreed that, if tributary inflow in substantial amounts occurred during the rising or falling limbs of a main stem hydrograph but not during the period of the crest, the cresting time and, hence, the crest travel time, were unaffected.

One of the fundamental tools used in the author's analyses was the unit hydrograph for the local area. If runoff, as evidenced by rainfall records, did not occur in the local area for some specific time before the downstream crest, it was assumed that the crest travel time was not changed. Furthermore, given a main stem crest with a reasonably large amount of peakedness, tributary inflow, if it were relatively steady, would not necessarily change the downstream cresting time appreciably even though it substantially augmented the downstream crest flow.

The author regrets that King did not have the opportunity to study the data presented by the author for the Verdigris and Neosho Rivers, since he feels that the data there are of a high order of quality. If the Van Buren to Dardanelle data were unsupported, they might be considered inconclusive. However, if they are considered in conjunction with other data, they add their weight to the author's thesis.

The author is not able to comment on King's estimates as to crest travel times. The author's crest travel times are not, however, his own determinations. During the period of record used, both Van Buren and Dardanelle had water stage recorders. Rating curves and tables were used as derived by the stream gaging agencies concerned, and included the loops and shifts used by those agencies. One of the pressing reasons why flows were necessarily used in this reach was the discrepancy noted between the 1943 and 1945 stages and flows. Although the flows during these floods are undoubtedly somewhat inexact, there can be little doubt that the 1943 flows were higher than in 1945. There were large levee breaks at and near Van Buren shortly before the crest of May 12, 1943, which, of course, affected the crest of May 23 as well. The effects of the levee breaks at Van Buren are clearly discernible on the recorder trace. Examination of Figure 3b will show that if the two 1943 crests are increased about two feet, the crest stage travel time points would then assume the same shape as the crest flow travel times in Figure 1.

The discrepancy at Ozark during the first rise in May, 1943, is, in the author's opinion, attributable to error at Ozark. The data at Ozark were, after all, taken by a layman without the assistance of a stage recorder, whereas the data at Van Buren and Dardanelle were recorded and then scrutinized and analyzed by trained hydrographers who were fully aware of the importance of the data.

REVIEWS , ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

SEGRÉ, E. (Editor), P. MORRISON, and B. T. FELD, Experimental Nuclear Physics, v. 2, John Wiley and Sons, 600 pp., 1954, $12.00.

Although Volume 1 of Experimental Nuclear Physics is divided into five parts, this second volume is composed of only two parts. These are Part VI, A survey of nuclear reactions, by P. Morrison; and Part VII, The neutron, by B. T. Feld. Part VI is further divided into 11 sections each containing several parts, and Part VII is similarily divided into five sections.

Part VI begins with a fairly detailed introduction to the laws of conservation of energy and momentum, and a general discussion of the types of nuclear reactions. This is followed by a discussion of nuclear models, level widths, cross sections, and the dispersion theory. Particular attention is given in succeeding sections to nuclear reactions, fission, and finally nuclear reactions at high energy.

Part VII summarizes the major aspects of neutron physics. Feld gives a general survey of the discovery, properties, and interactions of neutrons with nuclei, together with the basic theory governing these interactions. He discusses reactions according to neutron energies and also according to the mass of the target nuclei involved. The second section of this part is a rather complete review of neutron sources, detectors, and techniques for studying nuclear phenomena. The author next considers the diffusion and slowing down of neutrons in bulk matter, with emphasis on the mathematical methods used. Finally, under the general heading of coherent scattering phenomena, he discusses neutron scattering, diffraction, and polarization.

The material in this volume admirably complements that of Volume 1. As in the previous volume the text is adequately documented with quantitative experimental data and illustrations. An attempt has been made to provide enough background information so as to make the book useful to those in borderline fields as well as to nuclear physicists. The book certainly will be helpful to students and teachers of nuclear physics both as a text and as a reference work.

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NOTES AND PERSONALIA

NOTES

Corrigenda--In the February, 1954, issue, in the paper by Serge A. Korff, page 104, Eq. (3), the second n should be N.

In the April, 1954, issue, in the paper by John T. Pettit, page 194, Eq. (10), $\bar{r}_e/R$ (the left-hand term) should read $\overline{r_e/R}$.

In the same issue, in the program abstracts, page 378, (4) by Garniss Curtis, Howel Williams, and Werner Johle, there are two corrections. In the fifth line of the abstract, statement should read ". . . hypothesis of a sill under the valley floor." In the twelfth line, it should read ". . . in the rhyolitic streaks."

Dedication of Laboratory of Oceanography and Oceanographic Convocation, June 21-24, 1954--The Office of Naval Research will dedicate its new Oceanographic Laboratory, adjacent to the Woods Hole Oceanographic Institution, on June 21. The Laboratory is a three-story, reinforced-concrete and brick structure which will be operated under contract with the Woods Hole Oceanographic Institution. On the three days following the dedication ceremonies, an Oceanographic Convocation will be held to encourage the presentation and discussion of stimulating ideas and creative work in the broad field of oceanography. It is anticipated that about 30 papers will be presented by distinguished scientists from all over the world. The arrangements for the Convocation are under the direction of the National Research Council, and further details may be secured by addressing H. R. Gault at the Council, 2101 Constitution Avenue, Washington 25, D. C.

Shell Fellowship Committee--The research and fellowship program of the Shell Fellowship Committee on behalf of the Shell Chemical Corp., Shell Development Co., Shell Oil Co., and Shell Pipe Line Corp. has been expanded for 1954-1955 by 48 pct to a total of $263,500. Under the grant program, each grant of $5000 for a specific department is accompanied by an unrestricted grant to the school of $2500. This accounts for the major increase in the total amount. Forty-nine fellowships totaling $121,000 are included in the program. The funds are made available to a selected list of schools, which, in turn, make the selection of the fellows. Details may be secured by addressing the Shell Fellowship Committee, 50 West 50th Street, New York 20, New York.

Fifth Conference on Coastal Engineering--This Conference will be held at the Ecole National d'Electrotechnique et d'Hydraulique in Grenoble, France, September 8-11, 1954. Inquiries regarding the Conference should be addressed to M. R. René Frappat, who is General Secretary of the Conference, at Palais de l'Université, Grenoble, France. The Conference immediately precedes the Tenth General Assembly of the International Union of Geodesy and Geophysics which is being held in Rome, Italy, September 14-25, 1954.

First International Instrument Congress and Exposition--This will be held in Philadelphia, September 13-25, 1954, under the sponsorship of the Instrument Society of America. Details may be secured from the Director of the Congress, Richard Rimbach, 921 Ridge Avenue, Pittsburgh 12, Pennsylvania.

Fiftieth Anniversary of the Seismological Observatory of John Carroll University--The Fiftieth Anniversary of the Observatory will be held October 14, 1954, in the University Auditorium in Cleveland. It is planned that a Symposium on Applied Geophysics will be presented. Details may be secured by writing to Rev. Henry F. Birkenhauer, S. J., John Carroll University, Cleveland, Ohio.

Scholarship program of Magnolia Petroleum Co.--Scholarships are being continued in 17 universities for undergraduate students entering the senior year of their studies in geophysics, geology, and petroleum engineering. Details may be secured by writing to the Magnolia Petroleum Co., Magnolia Building, Dallas, Texas.

International science centers--The Cooperative Research Foundation is establishing these centers in cooperation with state and local academies of science to provide local facilities for scientific visitors from abroad, especially those whose visits to the United States are sponsored by private interests. The main purposes are to facilitate relations between the visitors and scientists of the region, to serve as a coordinating agency for international scientific activities, and to offer general assistance to the visiting scientists. The plan was developed jointly by the Foundation and the Office of International Relations of the National Research Council. The first such center has been established in San Francisco in cooperation with the California Academy of Sciences, Golden Gate Park, San Francisco, Calif., from which more information regarding the plan may be secured.

Napier Shaw Memorial Prize--The Royal Meteorological Society has announced the first competition for the Napier Shaw Prize of a hundred pounds sterling for an original essay on The Energetics of the General Circulation. The Prize has been established to commemorate the recent centenary of the birth of Sir Napier Shaw. The essays, in triplicate, must be in the Society's office not later than March 4, 1956. Details may be secured by writing to the Society at 49 Cromwell Road, London, S. W. 7, England.

Meteorological meeting in honor of G. Hellmann--The Meteorologische Gesellschaft of Hamburg is planning a three-day program October 4-6, 1954, in honor of the centennial of the birth of G. Hellmann, and is requesting brief contributions for the occasion. These should be forwarded by July 1, 1954. Details may be secured from M. Rodewald, Meteorologische Gesellschaft, Bernhard Nocht Str. 76, Hamburg 4, Germany.

National Science Foundation Panel on Minerals Research--The Foundation has recently established an Advisory Panel on Minerals Research with members from the mining and petroleum industries, universities, and government. Among the members are Alan Bateman of Yale University, Maurice Ewing of Columbia University, Paul D. Foote of Gulf Research and Development Co., L. C. Graton of Harvard University, Thomas Nolan, W. W. Rubey, and William E. Wrather of U. S. Geological Survey, Louis B. Slichter of University of California, and John Vanderwilt of Colorado School of Mines.

Canadian Geophysical Bulletin--Volume 6 of the Canadian Geophysical Bulletin has recently appeared. This gives a discussion of recent Canadian work in all fields of geophysics, and a bibliography of Canadian geophysical publications and works of which Canadians are authors.

Grants of the National Science Foundation--The Foundation has recently announced 159 grants in support of science totaling $1,359,000. Of these, ten are for projects in various fields of the Earth sciences, with others bearing heavily on geophysics in engineering, physics, biology, and other fields.

Fifth Alaska Science Conference--The Conference will be held September 7-10, 1954, at Anchorage, Alaska. Programs are planned for various fields, including the physical sciences, engineering, and agriculture and biology. Details may be secured by writing to Troy L. Péwé, Secretary, Alaska Division, American Association for the Advancement of Science, Box 4004, College, Alaska.

Survey of graduate student population--The National Science Foundation is undertaking a study of the financial support available to students for graduate work in 500 colleges and universities. This is one of a series of studies that the Foundation is making into the various phases of the scientific activities, resources, and needs of the country.

Postdoctoral fellowships of the National Science Foundation--The Foundation has recently announced the award of 79 postdoctoral fellowships of which two were in the Earth sciences, 13 in physics and astronomy, and one in engineering. There were 461 applicants. The number awarded is a substantial increase over the 42 selected a year ago. Announcement covering the program for 1955-1956 will be made by the Foundation about October 1, 1954.

PERSONALIA

Chas. G. Bates, Deputy Director, Division of Oceanography, U. S. Navy Hydrographic Office, was given the President's Award of the American Association of Petroleum Geologists for the paper on Rational Theory of Delta Formation published in the Bulletin of the Association in September, 1953.

Percy W. Bridgman, Higgins University Professor of Physics, Harvard University, with which he has been associated for over 50 years, is retiring at the end of the academic year now closing.

Lyman J. Briggs, Director Emeritus of the National Bureau of Standards and Chairman of the Research Committee of the National Geographic Society, has been given the Merit Award of the American Society of Sanitary Engineering for his contribution toward the advancement of sanitation in his relation to the basic research work on plumbing systems by the National Bureau of Standards. He was subsequently honored by the AAAS, which has devoted the May issue of the Scientific Monthly to a series of papers by his colleagues, and by the Washington Academy of Sciences, which arranged a testimonial for his eightieth birthday on May 7, 1954.

Randolph W. Chapman, formerly Professor of Geology at Johns Hopkins University, has been appointed Chairman of the Department of Geology at Trinity College.

Nicholas Feodoroff, Professor of Hydraulics at Manhattan College, has been awarded the Medal of French Renaissance of the French Government for his scientific achievements.

Edgar E. Foster, formerly of the Bureau of Reclamation on studies of hydrologic and economic water resources, has opened an office in Denver for consulting and development work in relation to water resources. His office is affiliated with the Kuljian Corp. of Philadelphia.

George Gamow, Professor of Physics at George Washington University, is on leave, serving as Visiting Professor of Physics at the University of California at Berkeley.

Jack B. Graham, formerly of the U. S. Geological Survey, has joined the staff of Leggett and Brashears, Consulting Ground-Water Geologists in New York.

Walter L. Huber, Consulting Engineer of San Francisco, Calif., has been designated by President Eisenhower as Presidential Adviser for the Arkansas, White, and Red River Basin Survey.

John B. Lucke, Professor of Geology, University of Connecticut, has taken over duties as Director of the Connecticut Geological and Natural History Survey, succeeding Edward L. Troxell, who has retired.

Kirtley F. Mather, Professor of Geology at Harvard University, is retiring at the end of the academic year just closing. He had been associated with Harvard University since 1924.

C. F. Merriam of the Pennsylvania Water and Power Co. in Baltimore has been elected President of the American Congress of Surveying and Mapping.

Brian O'Brien, Vice President of the American Optical Co. and Chairman of the Division of Physical Sciences of the National Research Council, has been elected a member of the National Academy of Sciences.

W. Dudley Parkinson of the Department of Physics, Fordham University, has accepted a position as Senior Geophysicist in the Australian Bureau of Geology, Geophysics, and Mineral Resources. He will leave for his new work in early July.

J. S. Pluta has resigned his position with the Standard Oil Co. of Texas and has accepted a position as Geophysical Supervisor with the Century Geophysical Corp. with headquarters in Tulsa, Oklahoma.

N. B. Sauve of the Standard-Vacuum Oil Co. with headquarters in New York has taken up duties with the Vacuum Oil Co. in Melbourne, Australia.

R. F. A. Studds, Director of the U. S. Coast and Geodetic Survey, has been reappointed for a four-year term.

R. Maurice Tripp has resigned as an officer of Research, Inc., to devote more time to the scientific aspects of mineral exploration, particularly the development of new methods and techniques. He will continue his work with the company as a consultant.

Ernest H. Vestine, Chairman, Section of Statistical and Analytical Geophysics, Department of Terrestrial Magnetism, Carnegie Institution of Washington, has been elected a member of the National Academy of Sciences.

F. Alton Wade has resigned as Professor of Geology of Miami University to accept the position of Professor and Head of the Department of Geology of the Texas Technological College.

Frank L. Weaver, Chief of the Division of River Basins, Bureau of Power, Federal Power Commission, is on leave of absence and is engaged on work of the Hoover Commission on Organization of the Executive Branch of the Government.

Transactions, American Geophysical Union Volume 35, Number 3 June 1954

THIRTY-FIFTH ANNUAL MEETING (1954)

MINUTES, GENERAL ASSEMBLY AND SECTION MEETINGS

SMOKER

A Smoker was held in the Ball Room of the National Press Club, National Press Building, Fourteenth and F Streets, N. W., Washington, D. C., on Monday, May 3, 1954, starting at 20h 00m. About 225 were in attendance. No program was presented, and the gathering was entirely informal, providing opportunity for those in attendance to form ever-changing small discussion groups.

EVENING SESSION

The Evening Session of the Thirty-Fifth Annual Meeting was called to order by President James B. Macelwane at 20h 00m, Tuesday, May 4, 1954, in the Lecture Room of the National Academy of Sciences, 2101 Constitution Avenue, Washington, D. C. Over 200 were in attendance. After appropriate welcoming remarks, President Macelwane presented Joseph Kaplan of the University of California, Chairman of the U. S. A. National Committee for the International Geophysical Year, who spoke briefly on plans for the Geophysical Year, 1957-1958, and requested the AGU, its Sections, and Committees to join fully into the program.

President Macelwane then introduced William C. Krumbein of Northwestern University, who presented the Lecture of the evening entitled Applications of Statistics in the Earth Sciences.

Following this, President Macelwane called on Harry H. Hess to present the citation of Richard Montgomery Field as the Sixteenth Recipient of the William Bowie Medal. President Macelwane then made the presentation, following which the recipient responded. The proceedings are set forth in the opening pages [pp. 389-390] of this issue.

Closing the session, President Macelwane then read the following telegram which was sent to Honorary President John A. Fleming, who has been ill in Nashville, Tennessee:

> On this Bowie Medal evening, your many friends and admirers in the American Geophysical Union send greetings and best wishes. We want you to know that our thoughts are with you more than ever.

The session then adjourned, and was followed by an informal social hour, with refreshments, in the Auditorium of the National Academy of Sciences.

GENERAL ASSEMBLY: SYMPOSIUM AND BUSINESS MEETING

The General Assembly was called to order by President Macelwane at 14h 00m, Wednesday, May 5, 1954, in the Auditorium of the National Academy of Sciences. Over 200 were in attendance. The President turned the chair over to John N. Adkins, Chairman of the Committee on Meetings, who proceeded with the papers of the Symposium on Geophysical Models as listed in the Program [p. 354] except that it was not possible for W. S. Von Arx to be in attendance and thus paper (6) was omitted. During the session, there was brief discussion from the floor.

Following the Symposium, President Macelwane resumed the chair and called the Business Meeting to order. The minutes of the Thirty-Fourth Annual Meeting [see Trans. v. 34, pp. 502-505] were approved.

Report of the General Secretary--General Secretary Marble briefly summarized activities since the Thirty-Fourth Annual Meeting, pointing out that these are reported in connection with the minutes of the meetings of the Executive Committee of November 28, 1953 [see Trans., Apr., 1954, pp. 338-348], and May 2-5, 1954 [to be published in the August, 1954, issue of the Transactions]. He announced the total formal registration at the Thirty-Fifth Annual Meeting as 874, with perhaps in excess of 1000 in attendance.

A recapitulation of the changes in membership since May 1, 1953, is as follows:

Membership, May 1, 1953	5000	
New members, May 1, 1953, to May 1, 1954	374	
Reactivated	4	5378
Resignations	118	
Deceased	30	
Dropped	179	
Inactive	11	338
Membership, May 1, 1954		5040

The names of those deceased are listed in the reports of meetings of the Executive Committee, and brief obituaries are carried in the news items of the *Transactions*.

Reports of Standing Committees

Meetings--Chairman John N. Adkins announced the dates for the Thirty-Sixth Annual Meeting as May 2-4, 1955.

Reports of other Standing Committees were not presented; they will be published in the *Transactions*.

Reports of Special Committees

Resolutions--Chairman E. H. Vestine presented eight resolutions, all of which were unanimously adopted, as follows:

(1) RESOLUTION IN APPRECIATION OF THE SERVICES OF K. HILDING BEIJ

WHEREAS, K. Hilding Beij has served the American Geophysical Union as Secretary of the Section of Hydrology for fifteen years and as General Secretary of the Union for six years, and

WHEREAS, K. Hilding Beij has been devoted to the advancement of geophysics and to the best interests of the American Geophysical Union, and

WHEREAS, K. Hilding Beij has represented this country in several capacities at the proceedings of the International Union of Geodesy and Geophysics, and

WHEREAS, The American Geophysical Union is indebted to K. Hilding Beij for over twenty years of continuous service, therefore be it

RESOLVED, That the President and the General Secretary shall convey, in appropriate form, the appreciation of the Union to Mr. Beij for these valued services.

(2) RESOLUTIONS OF THANKS FOR THE USE OF FACILITIES

WHEREAS, The National Academy of Sciences and the United States Public Buildings Administration have provided the use of meeting rooms and other services for the Thirty-Fifth Annual Meeting of the American Geophysical Union, therefore be it

RESOLVED, That the American Geophysical Union express its great appreciation of this cooperation, extended over many years, and instructs the General Secretary to express the thanks of the Union to the appropriate officials.

(3) RESOLUTION OF THANKS TO THE UNIVERSITY OF SOUTHERN CALIFORNIA

WHEREAS, The success of the Thirty-Second Regional Meeting at Los Angeles, California, on January 29-30, 1954, was due in large part to the space and facilities generously provided by the University of Southern California, therefore be it

RESOLVED, That the thanks of the American Geophysical Union be extended to the University of Southern California for the use of their meeting rooms and other facilities, and that the General Secretary be instructed to forward a copy of this resolution to Dr. Fred D. Fagg, Jr., President.

(4) RESOLUTION OF THANKS TO THE CARNEGIE INSTITUTION OF WASHINGTON

WHEREAS, The Carnegie Institution of Washington has for many years provided office space for the American Geophysical Union, without which the Union could not adequately function, therefore be it

RESOLVED, That the American Geophysical Union express its deep appreciation of this continued assistance and instructs the General Secretary to express its thanks to the appropriate officers of the Carnegie Institution of Washington.

(5) RESOLUTION REGARDING LUNAR OBSERVATIONS

WHEREAS, New techniques of high accuracy have been developed in recent years for observing the Moon, for calculating its position and motion, and for mapping the lunar profile, and

WHEREAS, Results of fundamental importance to geodesy will accrue through utilization of these techniques, therefore be it

RESOLVED, That full use should be made of these techniques and that present programs for the extension of triangulation which will furnish the needed geodetic data for the base-line stations be completed and the results made available as soon as possible.

(6) RESOLUTION REGARDING STRONG-MOTION SEISMOGRAPHS

WHEREAS, The strong-motion seismographs of the U. S. Coast and Geodetic Survey provide practically the sole means of obtaining authentic information on seismic wave motion in the central regions of strong earthquakes, and

WHEREAS, Complete data would be of great value in studying various aspects of the origin and propagation of seismic waves, energy distribution, and the evaluation of earthquake intensity, and

WHEREAS, The longer period waves are often the waves of greatest amplitude registered on a seismograph, therefore be it

RESOLVED, That the American Geophysical Union express the hope that the U. S. Coast and Geodetic Survey will include in its studies of destructive earthquake motion all ultra long-period waves as well as the shorter period waves which have special significance to the structural engineer, and be it further

RESOLVED, That copies of this resolution be sent to the Secretary of Commerce and the Director of the U. S. Coast and Geodetic Survey.

(7) RESOLUTION ON TIME-SIGNAL SERVICE

WHEREAS, There is a vital need in all seismological work for accurate time service, and

WHEREAS, The time service maintained by the U. S. Naval Observatory, the Naval Communications Service, and the National Bureau of Standards has been of great use in this work, therefore be it

RESOLVED, That the American Geophysical Union express its appreciation of the valuable scientific cooperation and reiterate its desire for the continuance of this time-signal service, and be it further

RESOLVED, That copies of this resolution be sent to the Secretary of the Navy, the Director of Naval Communications, the Superintendent of the Naval Observatory, the Secretary of Commerce, and the Director of the National Bureau of Standards.

(8) RESOLUTION ON COMMUNICATIONS SERVICES

WHEREAS, The Secretary of Commerce, in cooperation with the Foreign Service of the United States, the officers of the Foreign Service, and Foreign Service Operations Division of the Office of International Trade, have made available their special telegraphic facilities for transmitting teleseismic data to the U. S. Coast and Geodetic Survey, and

WHEREAS, The data have greatly enhanced the earthquake location program of that Survey, and

WHEREAS, The data have been made available by the Survey to seismologists throughout the world to aid in the more thorough analysis of their records, therefore be it

RESOLVED, That the American Geophysical Union express its appreciation for this valuable contribution to seismological research, and be it further

RESOLVED, That copies of this resolution be sent to the Secretary of Commerce, the Director General of the Foreign Service of the United States, the Foreign Service Operations Division of the Office of International Trade, and officers of the Foreign Service at the following stations: Djakarta, Java; Bombay, India; Brisbane, Australia; Copenhagen, Denmark; Guatemala City, Guatemala; Lima, Peru; Malaga, Spain; Mexico City, Mexico; Perth, Australia; Rome, Italy; Santiago, Chile; Strasbourg, France; Sydney, Australia; Tananarive, Madagascar; Pretoria, Union of South Africa; Wellington, New Zealand; and Dublin, Ireland.

Adjournment--The meeting adjourned at 16h 47m.

JOHN PUTNAM MARBLE, General Secretary
WALDO E. SMITH, Executive Secretary

APPENDIX A--MINUTES OF THE ANNUAL MEETING OF 1954, SECTION OF GEODESY, AMERICAN GEOPHYSICAL UNION

President Hoskinson called the meeting to order in the Lecture Room of the National Academy of Sciences at 09h 05m on May 3, 1954. There being no objection from the floor, and no corrections received, the President declared the minutes of the 1953 meeting approved as published in the Transactions [v. 34, p. 505, 1953].

The President announced the appointment of a Committee on Resolutions including C. A. Whitten (Chairman), A. D. Sollins, and Floyd W. Hough, and stated that a Program Committee would be appointed in the near future.

The scientific session proceeded as published in the Program [p. 355] except that paper (8) was read after paper (3). After paper (8) was read, the Committee on Resolutions introduced a resolution on new techniques of observing the Moon, calculating its position and motion, and mapping its profile. This was approved by the Section and forwarded to the Resolutions Committee of the Union [see Resolution (5) above].

Papers by T. J. Kukkamäki and W. A. Heiskanan, who could not be present, were read by W. D. Lambert and A. D. Sollins, respectively.

Approximately 115 members and guests attended the meeting.

The meeting adjourned at 12h 34m.

FRANK L. CULLEY, Secretary

APPENDIX B--MINUTES OF THE ANNUAL MEETING OF 1954, SECTION OF SEISMOLOGY, AMERICAN GEOPHYSICAL UNION

The Thirty-Fifth Annual Meeting of the Section of Seismology was held on May 4 and 5, 1954. The first session was called to order at 14h 00m by President Heinrich at the State Department Auditorium. The minutes of the 1953 meeting were approved as published in the Transactions [v. 34, p. 505, 1953].

The President appointed a Resolutions Committee (L. M. Murphy, Chairman; V. G. Gabriel, and Joseph J. Lynch).

L. M. Murphy presented two resolutions and Frank Neumann presented one for action by the Section. These were approved and forwarded to the Union [see Resolutions (6), (7), and (8) above].

As there was no further business, the business session was adjourned and was followed immediately by the scientific session shown on the Program [see p. 355].

J. A. PEOPLES, JR., Secretary

APPENDIX C--MINUTES OF THE ANNUAL MEETING OF 1954, SECTION OF METEOROLOGY, AMERICAN GEOPHYSICAL UNION

The Thirty-Fifth Annual Meeting of the Section of Meteorology was held on May 3-5, 1954, in the Auditoria of the General Services Building, the National Academy of Sciences, and the Department of State. It is estimated that around 200 members and guests attended the seven sessions of the meeting.

The business session was opened at 09h 00m, May 3, 1954, by President Phil E. Church.

Since no corrections were received, the Chairman declared the minutes of the Thirty-Fourth Annual Meeting of the Section of Meteorology approved as published in the Transactions [v. 34, p. 506, 1953]. The Chairman then appointed a Committee on Resolutions (P. F. Clapp, Chairman; Werner A. Baum, and Herbert Riehl).

A brief report was given by the Meteorological Editor, Charles S. Gilman. Other committee reports were referred to by title only.

The scientific program of the seven sessions consisted of the presentation and discussion of papers listed in the Program [pp. 355-356]. Changes in the Program are as follows:

(1) The panel for discussion on Aviation Weather Services as given on page 356 should be corrected to read: Moderator: Jerome Lederer; Panel Members: Nicholas H. Chavasse, Jean Dubuque, Richard Jamison, Max Karant, J. C. S. McKillip, Daniel O'Keefe, Francis W. Reichelderfer, and Joe Tippetts.

(2) The final paper (23) on the Program for May 5, 1954, should be credited to William C. Spreen.

(3) Jerome Spar did not participate in the panel discussion on the Mechanism of Pressure Changes as shown on the Program [p. 355].

(4) Donald House did not participate in the panel discussion on Quantitative Precipitation Forecasting as shown on the Program [p. 356].

(5) The following films were presented in addition to the papers listed on the Program:

Alan Faller: Models of general circulation with a demonstration of fronts and frontal waves in the atmosphere (following paper (16), morning of May 4).

David K. Todd: Salt water intrusion (following Panel on Quantitative Precipitation Forecasting, afternoon of May 4).

WOODROW C. JACOBS, Secretary

APPENDIX D--MINUTES OF THE ANNUAL MEETING OF 1954, SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY, AMERICAN GEOPHYSICAL UNION

The Thirty-Fifth Annual Meeting of the Section of Terrestrial Magnetism and Electricity of the American Geophysical Union was held on May 3 and 4, 1954. The first session was called to order at 09h 10m on Monday, May 3, in the Auditorium of the State Department by President Victor Vacquier. There were approximately 65 members and guests in attendance. The minutes of the previous meeting were approved as published in the Transactions [v. 34, p. 506, 1953].

President Vacquier opened the discussion regarding a possible change in the name of the Section. It was pointed out that the International Union of Geodesy and Geophysics is considering a change in the name of the International Association of Terrestrial Magnetism and Electricity to one which specifically mentions physics of the upper atmosphere. In the lively discussion which followed both sides of the question were presented by various Section members. However, no conclusions were reached.

After routine announcements the scientific program was begun in accordance with the Program as printed [see p. 357]. Vice President Henry Joesting presided while paper (7) was presented by President Vacquier. The session adjourned at 11h 52m.

The second session was convened at 14h 00m on May 3, in the Auditorium of the National Academy of Sciences. After routine announcements the technical program was given as published [see p. 357]. The meeting was adjourned at 16h 30m.

The third session of the Section was held jointly with Commission 3 of the U. S. National Committee of the International Scientific Radio Union. This session was convened at 14h 10m on May 4 in the East Building at the National Bureau of Standards. James C. W. Scott presided. In addition to the published technical program [see p. 357], paper (21) was given by N. C. Gerson on Ionospheric Vertical Incidence Records Obtained Over the North Pole on March 15, 1954. The meeting was adjourned at 17h 28m.

L. R. ALLDREDGE, Secretary

APPENDIX E--MINUTES OF THE ANNUAL MEETING OF 1954, SECTION OF OCEANOGRAPHY, AMERICAN GEOPHYSICAL UNION

The Thirty-Fifth Annual Meeting of the Section of Oceanography was called to order by President Richard Fleming at 14h 00m on May 4 in the Auditorium of the General Services Building. Since no corrections had been received, the President declared the minutes of the 1953 meeting approved as published in the Transactions [v. 34, p. 507, 1953].

A report on plans for the International Geophysical Year 1957-1958 was made by Secretary Pritchard. Programs in the field of Oceanography which have been presented to the U. S. National Committee for the IGY were briefly described. It was pointed out that the Section has taken no official stand regarding the oceanographic program for IGY.

The President announced that the Joint Committee on the Interrelations between Meteorology and Oceanography, as established at last year's meeting by joint action of the Sections of Oceanography and Meteorology and the American Meteorological Society, had been functioning under the chairmanship of C. C. Bates. This Committee sponsored a Symposium on the Interaction of the Sea and Atmosphere at the Baltimore Meeting of the AMS. It was suggested that the Joint Committee consider holding a symposium on this subject at next year's AGU Annual Meeting.

It was also announced that tentative plans had been made to hold a symposium on post-war oceanographic expeditions as part of the Section program next year.

The President expressed appreciation to C. C. Bates for his efforts in planning the session on Oceanographic Motion Pictures held on the afternoon of May 3, in which the Program deviated substantially from that printed on page 358, and was as follows:

General
- (a) Activities of the U. S. Coast and Geodetic Survey; sound; color (USC and GS film)
- (b) Weather men of the sea; sound; color (USCG film)
- (c) Activities of the Chesapeake Bay Institute; black-and-white
- (d) Operation Ski-Jump II; sound; color (USN film MN-7478)

Technical
- (e) Four experiments in hydraulics; sound; color; U. S . Bureau of Standards
- (f) Ocean tides; Narrator: William E. Maloney, U. S. Navy Hydrographic Office; silent; black-and-white (MacQueen film)
- (g) Model studies of ocean currents; silent with titles; color (William S. von Arx, Woods Hole Oceanographic Institution)
- (h) Outcrop of the inshore edge of the Gulf Stream as seen from the air; silent with titles; color (William S. von Arx, Woods Hole Oceanographic Institution)
- (i) Study of cumulus clouds entering the jet stream; silent with titles; color (Joanne S. Malkus and Claude Ronne, Woods Hole Oceanographic Institution)
- (j) Rough seas viewed from the Caryn and the Atlantis; silent (Woods Hole Oceanographic Institution)
- (k) Identification of sea ice; sound; color (USN film MN-7419-B)
- (l) Wave impact on piles; Narrator: Rudolph Savage, U. S. Beach Erosion Board; silent with titles (Dept. of Oceanography, Texas A and M College)

The business meeting was then adjourned and was followed by the scientific session as shown on the Program [see p. 359]. Prior to the business meeting, the Section had also met on the morning of May 4 in joint scientific session with the Section of Meteorology.

DONALD W. PRITCHARD, Secretary

APPENDIX F--MINUTES OF THE ANNUAL MEETING OF 1954, SECTION OF VOLCANOLOGY, AMERICAN GEOPHYSICAL UNION

The business meeting was called to order by President Foshag at 14h 05m, May 4, 1954. The minutes of the previous meeting were accepted as published in the Transactions [v. 34, p. 507, 1953]. There being no committee reports or other business, the chair recognized H. H. Hess, who was concerned that the professional interests of the active members of the Section were far broader than the title of the Section would indicate. This had been common knowledge for a number of years, but pressure for a name change which would acknowledge the broader scope of the Section's interests had now reached the point where action seemed imperative. He therefore moved that the Section change its name to Section of Volcanology Geochemistry, and Petrology. It was pointed out that according to the Constitution of the Union the proper procedure was to request the Union's Executive Committee to initiate action permitting the change. Hess amended his motion accordingly, and it was seconded by J. F. Schairer. Schairer and E. G. Zies then supported the motion strongly. There being no further discussion, the amended resolution was unanimously approved by voice vote. It was the sense of the meeting that the Section officers should present the proposal to the Union's Executive Committee at the first opportunity. (This has now been done, and the matter has already been referred to the Committee on By-Laws for appropriate action.)

The technical program [see p. 359] began at 14h 20m and adjourned at 17h 00m. The second technical session was called to order at 09h 05m on May 5 and adjourned at 11h 45m. Both meetings were well attended and marked by lively discussion. This was the longest and best scientific program we have had in a number of years; we are all indebted to the Chairman of the Program Committee, Ralph Cannon.

FELIX CHAYES, Secretary

APPENDIX G--MINUTES OF THE ANNUAL MEETING OF 1954, SECTION OF HYDROLOGY, AMERICAN GEOPHYSICAL UNION

President Harold G. Wilm called the meeting to order at 09h 00m, May 3, 1954, and announced that the business meeting would be quite brief. Attention was called to the meeting of the International Union of Geodesy and Geophysics to be held in Rome, Italy, September 14-25, 1954. President Wilm announced that he and Secretary Harry F. Blaney, as well as others, expect to attend the Rome meeting and will represent the Section of Hydrology. Several hydrology papers are to be presented at the meeting.

President Wilm announced that selection of chairmen and members of all the Research Committees of the Section of Hydrology had been completed for the triennium.

The President called upon Walter B. Langbein to discuss a proposed resolution which was to be presented to the Union. The resolution recommended that the President and the General Secretary of the Union take appropriate action to convey to K. Hilding Beij the appreciation of the Union for his outstanding services during the past 20 years. Langbein read the resolution and said that after AGU officers had been given an opportunity to sign the resolution, it would be circulated for the signature of other members.

President Wilm called attention to the AGU Smoker to be held the evening of May 3; and to a 16-mm color film on Sea Water Intrusion to be shown at the Hydrology session on Tuesday, May 4, following the Panel Discussion on Quantitative Precipitation Forecasting, Present and Future.

There being no further business, President Wilm proceeded with the technical session, which was presented in accordance with the Program [see pp. 353-388, April, 1954, Transactions] except for the following:

(R2) Report by Frye was presented by Russell H. Brown.
(2) Paper by Hantush and Jacob was presented by title, as the authors found shortly before the meeting that it was impossible for them to attend.
(3) Paper by Waite and Thomas was presented by Thomas.
(6) Paper by Cushman and Halpenny was presented by Joseph T. Callahan.

The session adjourned at 11h 50m.

The Monday afternoon session was called to order at 14h 10m by President Wilm, who introduced William O. Field as Session Chairman. The program was followed with the following exceptions:

(R3) Report by Schiff was presented by Donald E. Whelan.
(R4) Report by Hoover was presented by Bernard Frank.
(R5) Report by Doneen was presented by Warren W. Hastings.
(R6) Report by Work was presented by William G. Shannon.
(R8) Report by Brater was presented by title.
(R9) Report by Bondurant was presented by Ralph N. Wilson.

The session adjourned at 16h 35m.

The morning session of May 4 was called to order by President Wilm at 09h 05m, who introduced Albert L. Cochran as Session Chairman. The program was followed with the exceptions noted below:

(12) The paper by Allen, Glover, Garstka, and Posz was presented by Victor A. Koelzer.
(13) The paper by Love was presented by James G. Osborne. A formal discussion of this paper was presented by Walter B. Langbein.
(14) Paper by Brown and Dunford was presented by Donald E. Whelan.
(R12) Report by Gottschalk was presented by Erwin C. Ford.
(16) Paper by Dunford was presented by Bernard Frank.
(17) Paper by Flaxman and Hobba was presented by Erwin C. Ford.

The session adjourned at 12h 10m.

The joint meeting with the Section of Meteorology on Tuesday, May 4, was called to order at 14h 10m by Albert K. Showalter, the Panel Moderator. A lively discussion by the panel members, and later by the audience, contributed to a very successful joint meeting.

Following the Panel Discussion, the previously announced 16-mm color film on Sea Water Intrusion was presented. The film, prepared as a research project by the University of California for the California Division of Water Resources, was made available for showing through arrangements with Prof. David K. Todd of the University of California.

The meeting adjourned at 17h 00m.

RALPH N. WILSON, Acting Secretary

APPENDIX H--MINUTES OF THE ANNUAL MEETING OF 1954, SECTION OF TECTONOPHYSICS, AMERICAN GEOPHYSICAL UNION

The business session was called to order at 09h 10m, May 4, 1954, in the Lecture Room, National Academy of Sciences Building, by President Birch. The minutes of the 1953 meeting were approved as published in the Transactions [v. 34, p. 509, 1954].

There being no further business, the scientific session of the Section [Trans., v. 35, p. 361, 1954] followed immediately.

JAMES T. WILSON, Secretary

SPECIAL ANNOUNCEMENTS

Tenth General Assembly of the International Union of Geodesy and Geophysics, Rome, Italy, September 14-25, 1954--Plans for this Assembly are in their final stages, and while about 100 are on the list from the United States to attend, there are probably others who have not yet advised the office of AGU of their plans. If you plan to attend, please advise the office of AGU without further delay. Let us also have word of your travel and lodging plans.

Plans for Regional Meeting (November 5 or 12, 1954) and Regional Organization in the North Pacific--At the request of members in the North Pacific Region [see Trans., v. 30, pp. 936-939, 1949], an ad hoc committee for the Region has been appointed as follows: C. C. McDonald (207 Federal Building, Tacoma, Washington), Chairman; Thomas H. Campbell; and Milton S. Sachs, with Frank Neumann, who is a representative from the Region on the Committee on Meetings, serving ex officio, and with the services of Norbert Leupold and M. J. Mundorff coopted by the Chairman. A Regional Meeting is tentatively planned to be held in Portland, Oregon, November 5 or 12, 1954. This will include a scientific or technological program as well as discussion of plans for formal organization. Interested persons should get into touch with the Chairman or a member of the Committee.

Attention is called to the fact that, though this activity is being initiated primarily in Hydrology, the door is at all times open for other Sections to join in the activity. Representation to this end should be made direct to the Committee, the appropriate Section officers, or to the office of AGU.

Thirty-Sixth Annual Meeting to be held May 2-4, 1955--The Thirty-Sixth Annual Meeting of AGU will be held in Washington, D. C., May 2-4, 1955 (Monday-Wednesday). This is a first call for titles and abstracts of papers, and for suggestions for symposia or other matters relating to the Meeting. Address your communications to the office of AGU or to the appropriate Section Secretary [see page 823 of the Transactions of October, 1953]. Watch SPECIAL ANNOUNCEMENTS in subsequent issues of the Transactions for further information.

Transactions, American Geophysical Union Volume 35, Number 3 June 1954

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To the Membership of the
American Geophysical Union

Dear Fellow Members:

I would like this to be considered a personal communication to each and every one of you, even though we are using the medium of the Transactions to get this message to you. The American Geophysical Union is traditionally interested in promoting the interdisciplinary cooperation of scientists and engineers in all of the geophysical fields and in the dissemination of scientific knowledge relating to geophysics to the widest possible circles. Our membership is currently about five thousand. But it is estimated that there are upwards of ninety thousand scientists and engineers in the United States whose work is connected in some manner with one or the other of the geophysical sciences. Thus we have enrolled only a small minority so far. Your officers desire, at all times, to be cognizant of the problems involved in widespread dissemination and to make improvements in every possible way in this effort. Therefore, we are writing to you to solicit your aid in the recognition and solution of these problems.

Our Transactions are now published bimonthly as they have been continuously since 1945, with the usual size of each number being 150-160 pages. Through our Editorial Committees we have striven during this interval to improve the quality of the papers, and we have at all times encouraged authors to reduce the normal tendency toward wordiness, which many of us have, in the effort to bring you more content in these pages. Despite this effort, however, our backlog in recent years has increased from a time-interval lag of about six months to almost twelve. We want to make every reasonable effort to reduce this interval to six months again in order that authors may have the satisfaction of prompt publication of their papers and that our member readers may have the advantage of the prompt availability of new knowledge. To do this will require increasing the size or the frequency of publication of our Transactions, which, of course, involves greater outlay in the way of publication costs. There seem to be only two ways of meeting this situation: (1) by the increase of individual dues, and (2) by an increase in membership sufficient to give us a greater volume at no increase in cost per member. We would also like to improve the format. One of the early steps in this would be the justification of the right-hand margin and possibly the reproduction of the Transactions in a two-column format instead of full-page width as at present.

Under the chairmanship of W. E. Hiatt, our Membership Committee is soon to undertake a project of requesting each of you to secure at least one more member, among your acquaintances, from the many who have qualifications for membership but are not currently members. On the back flyleaf of this issue, we are including a membership application form which you may use even in advance of this effort on the part of the Membership Committee. We are contemplating a new Membership Directory to be issued with the December issue, and prompt action with regard to application at this time will permit the inclusion of the names of new members in the forthcoming Directory. We realize that you may not now know who among your associates are currently members. The last list of members was issued in October, 1952, and this may be of some aid in this regard, especially if one considers the supplementary lists of new members published in April and October of 1953 and in June of 1954.

I most earnestly solicit your individual aid in regard to this matter.

Sincerely yours,

James B. Macelwane SJ

James B. Macelwane, President

TRANSACTIONS
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GRAVIMETRICALLY COMPUTED DEFLECTIONS OF THE VERTICAL IN OHIO

William M. Kaula

Abstract--Deflections of the vertical were computed for five points over a range of 100 km in central Ohio, using free-air anomalies out to 1500 km and isostatic anomalies, with corrections, for the rest of the Earth. For ξ at all five points, and for η at three points, agreement with the astronomically observed deflections was obtained to within 0″.67; errors in astronomic longitude are shown to cause disagreement in η at two points. The probable error of the gravimetrically computed deflection on the assumption of random variation of the mean anomalies of five-degree squares was computed to be ±0″.38; on the assumption of random variation of the mean anomalies of 30° squares, to be ±1″.15.

Introduction--The theoretical basis for computation of deflections of the vertical from gravity anomalies are the equations developed by VENING MEINESZ [1928]. The method of applying these equations used herein is essentially that developed by RICE [1952] in computing the deflections of the vertical at several points in the southwest. This investigation differs principally in the lesser accuracy of the local gravity field used; use of isostatic anomalies for distant areas, thereby necessitating computation of additional corrections; and an attempt to compute the accuracy of the gravimetric deflections considering the entire world gravity field.

Astronomic observations and data--In central Ohio there were available one point (Columbus) with astronomic latitude and longitude, observed by the U. S. Coast and Geodetic Survey in 1871, and two points (Conley and Barr) with astronomic longitude, observed by the U. S. Coast and Geodetic Survey in 1929. Observations were made with a pendulum astrolabe at Conley and Barr, and at two additional points (State and Stanforth). All these points are located on, or closely connected to, a first order arc of triangulation observed by the U. S. Coast and Geodetic Survey in 1928.

A personal-equation correction, obtained by comparison of the astrolabe longitudes with those already existing at Conley and Barr, was applied to the longitudes at State and Stanforth. The astronomic positions were reduced to sea level for systematic curvature of the vertical in the meridian, and also for curvature of the vertical due to anomalous masses [RICE, 1952]. No correction was made for the effect of condensation of the topography on the geoid, as implied by the free-air gravity reduction used. No correction was made for polar variation or for change of star catalogue, affecting all the old observations; nor for changes in the apparent place computation constants and lunar terms affecting the observations of 1871.

The deflections obtained from the astronomic observations and geodetic coordinates are with respect to the Clarke 1866 ellipsoid, North American 1927 datum. To transform the deflections from the Clarke ellipsoid to the International ellipsoid on which the gravity anomalies are based, the transformation equations of VENING MEINESZ [1951] were used. No correction was made for change of the datum, that is, for change in the deflections assumed at the origin, Meade's Ranch. The change found in the most likely solution of HAYFORD [1909] was less than 0″.3. RICE [1952] suggested a change of -1″.2 in latitude, but 0″.5 of this is due to the less accurate field beyond 628 km, and 0″.5 to the expansion of the world gravity field in spherical harmonics by JEFFREYS [1943] (see Table 1).

Gravity observations and reductions--Ideally, the distribution of the gravity stations should be such that each station makes an equal contribution to the probable error of the deflections computed therefrom. This distribution may be computed, given the errors of representation for the station spacings used, by use of the tables of SOLLINS [1947]. Each ring of stations should add an equal increment

$$dF = \int_{\psi_1}^{\psi_0} (df/d\psi) \sin \psi \, d\psi$$

Table 1--Astronomic-geodetic deflections

Station	Geodetic coordinates	Deflection, Clarke ellipsoid	Probable error astronomical observation	Ellipsoid change	Deflection, International ellipsoid
	° ′ ″	″	″	″	″
Conley	ϕ = 40 33 15.94	ξ = +2.90	±0.30	+0.150	+3.05
	λ = 83 08 08.09	η = +3.05	. . . .	-0.809	+2.25
Stanforth	ϕ = 40 14 26.64	ξ = +1.05	±0.30	+0.097	+1.15
	λ = 83 00 47.26	η = -1.75	±0.25	-0.810	-2.55
State	ϕ = 39 59 40.70	ξ = +0.4	±0.3	+0.059	+0.5
	λ = 83 00 54.58	η = -7.0	±0.25	-0.811	-7.8
Columbus	ϕ = 39 57 40.505	ξ = -0.12	. . . .	+0.050	-0.07
	λ = 82 59 57.08	η = -8.37	. . . .	-0.811	-9.18
Barr	ϕ = 39 38 57.47	ξ = +1.08	±0.40	-0.002	+1.08
	λ = 82 49 14.00	η = -0.97	. . . .	-0.813	-1.78

to the integral of the deflections, and then the number n of stations in each ring taken so that $(E_r/n)\,dF$ is kept fairly constant [HIRVONEN, 1953], E_r being the error of representation. Since such a distribution would have taken much more time to observe than was available, it was modified so that the station spacing increased in direct proportion to the distance from the deflection point until at 120 km it about equaled the spacing of pre-existing U. S. Coast and Geodetic Survey pendulum stations.

One hundred eighty-four gravity stations were observed with a Worden gravity meter. As many stations as possible were sited at bench marks; Paulin System altimeters were used to obtain the elevations at the others, taking the mean of the elevation from a preceding bench mark and that from a succeeding bench mark. As estimated from the manner of observation, and as checked by the readings at 12 stations reoccupied during the survey, the average probable error of the anomalies due to observational errors was less than ±0.2 mgal.

To obtain the gravity anomalies, a simple condensation of exterior matter on the geoid (Helmert's second method) was used. The terrain in central Ohio is sufficiently level so that the topographic correction is negligible (less than 0.3 mgal for all stations in this problem). The value of g on the Potsdam system was obtained from U. S. Coast and Geodetic Survey Pendulum Station 136 in Columbus, observed in 1914.

The free-air isoanomalies were plotted at a scale of 1:62,500 out to 15 km from each astronomic station; at a scale of 1:500,000 out to 200 km; on an azimuthal map at 1:8,780,000 (2°/inch) for what will be called the local area between latitudes 25° and 55° N and longitudes 65° and 100° W, excluding the four corner five-degree squares. For the rest of the Earth ("distant areas"), the mean isostatic anomalies for each five-degree square found by TANNI [1948] were plotted on an azimuthal map at 20° to the inch. These azimuthal maps give true distance and azimuth from latitude 40° N, longitude 83° W.

Gravimetric computation of the deflections--Out to a radius of 1406 km, the template system devised by RICE [1952] was used. The inner radius within which the gradient formula was used was taken as 657 m at all stations except State, where it was 554 m. All stations were computed out to 179.1 km. Beyond that limit the deflections for Station Columbus were taken to be the same as those at State, 3.2 km away. The computed deflections for various zones from 44 through 50, 179.1 to 541.5 km, for State and Stanforth were compared with those obtained by interpolation from Conley and Barr for these zones, but results were unsatisfactory. So Stations State and Stanforth were computed separately out to 836 km, through Zone 53. The deflections for Conley and Barr were computed out through Zone 57, or 1406 km, and deflections for intervening stations interpolated for the zones beyond 836 km.

The deflections due to the border area beyond 1406 km, but within the local area, were computed for Conley and Barr: For this purpose, the area was broken up into compartments bounded by the 1406-km circle and five-degree lines of latitude and longitude, and the area of each compartment estimated as a fraction of a five-degree square. These deflections differed only $0''.007$ in ξ between Conley and Barr, and were exactly equal in η.

For the general gravity field of the world, two principal sets of data exist: An expression of the free-air anomalies in seven terms of spherical harmonics up to the third degree by **JEFFREYS** [1943], and the mean Hayford (D = 113.7 km) isostatic anomalies for about 33 pct of the five-degree squares on the Earth's surface, by **TANNI** [1948]. Use of Jeffreys' spherical harmonic formula by transforming the ϕ, λ parameters to ψ, α parameters and integrating from a desired radius outward was considered, but dropped as too complicated mathematically. A more serious objection to the Jeffreys formula seems to be that using a field of wave-length 120° beyond a radius of only 12.5° might neglect an anomalous area of extent less than ten degrees, say, but still of appreciable effect on the deflection.

It was decided to utilize the data of **TANNI** [1948] for the distant areas. Having been compiled seven years later than Jeffreys' data, it has a broader empirical basis. To utilize these anomalies, it is necessary to transform the Vening Meinesz formula, since the element of area on the unit sphere is changed from $\sin\psi d\psi d\alpha$ to $\cos\phi d\phi d\lambda$. In this case, $d\phi$ and $d\lambda$ become five degrees, except in areas near the poles. The areas of the five-degree squares may be found by

$$q = (2\pi/n)\,(\sin\phi_N - \sin\phi_S)$$

where ϕ_N, ϕ_S are the latitudes of the northern and southern bounds of the square, n is the number of squares in that particular zone of latitude.

The azimuth α and distance ψ from latitude 40° N, longitude 83° W of each of the five-degree squares beyond 13° for which an anomaly differing from zero is given by Tanni were measured on the azimuthal map of the world to the nearest degree. The value of $df/d\psi$ from the table of **SOLLINS** [1947] was multiplied by the mean anomaly for the square, and then the values of $\Delta g\,(df/d\psi)\cos\alpha$ and $\Delta g\,(df/d\psi)\sin\alpha$ for each square were found by slide rule to the nearest unit. Next, the sum of these products for each zone of latitude was found, and this sum was multiplied by the q for the squares of the zone. Finally the deflections were computed as

$$\xi'' = (\csc 1''/2\pi G)\,\Sigma q\,\Sigma\,\Delta g\,(df/d\psi)\cos\alpha = +0''.163 \quad \ldots\ldots\ldots\ldots\ (1)$$

$$\eta'' = (\csc 1''/2\pi G)\,\Sigma q\,\Sigma\,\Delta g\,(df/d\psi)\sin\alpha = +1''.039 \quad \ldots\ldots\ldots\ldots\ (2)$$

The above deflections are what would exist due to the distant areas after the topography and Hayford isostatic compensation (D = 113.7 km) have been removed all over the Earth. What is required are the deflections which would exist due to the distant areas when a surface condensation of external topography prevails all over the Earth. This change from isostatic to free-air deflections entails two corrections: (1) replacing the Hayford compensation and adding a surface condensation within the local area will cause changes in the mean anomalies of the five-degree squares outside the local area, which changes will in turn affect the deflections computed from these mean anomalies; and (2) replacing the Hayford compensation and adding a surface condensation outside the local area which will affect the deflections due to distant areas directly.

The first requires finding for each five-degree square a correction to the mean anomaly, which correction will be the mean of the changes in anomalies all over the five-degree square when the Hayford compensation is replaced and a surface condensation added in place of the external topography within the local area. For this purpose the corrections for topography and compensation combined given by the tables of **HAYFORD** and **BOWIE** [1912] were used. This method neglects the difference of elevation of the station and the compartment, and the difference of attraction of the topography and its surface condensation. For the low elevations occurring in this problem, these differences are negligible.

The mean correction of a five-degree square will differ, in general, from the correction for the central point. To find the mean correction, corrections at points along profiles perpendicular to the boundary of the local area were computed. The corrections are negative for points at sea on the boundary, and positive for boundary points on land, but generally the correction changes to a maximum of much larger magnitude and of opposite sign within 18 km of the boundary, and retains the same sign throughout the rest of the profile: positive at sea, negative on land (see Fig. 1 and 2).

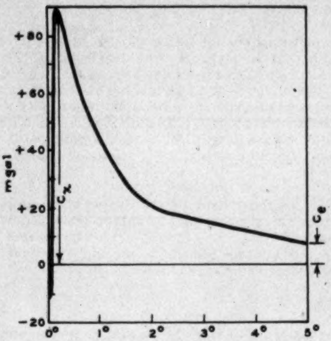

Fig. 1--Sea profile; corrections to isostatic anomalies, latitude 32.5°N from longitude 65° to 60° W

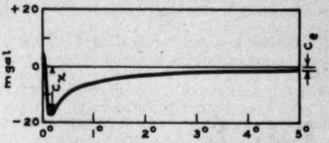

Fig. 2--Land profile; corrections to isostatic anomalies, latitude 37.5°N from longitude 100° to 105°W

The mean correction for a profile will be the area under the curve divided by the length of the profile. The mean correction for a five-degree square can then be found as an appropriately weighted mean of the corrections for several profiles across the square.

In application, corrections were computed only for those 30 five-degree squares touching on the local area. It was found that the mean correction for a profile could be expressed with sufficient accuracy in terms of the maximum point and the outer end point values of the profile

$$C_m = C_e + k\,(C_x - C_e) \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (3)$$

where C_m, C_e, and C_x are the mean, outer end, and maximum corrections respectively; k averages about 0.23 at sea, 0.17 on land. Thus, only two points need be computed for each profile. This computation was done using a 1:5,000,000 map, combining Zones A through N into one for purposes of estimating elevations.

For each five-degree square symmetrically placed with respect to the local area, only one profile was computed; for five-degree squares near the corners of the local area, three profiles were computed and a weighted mean taken for the square. The corrections for 13 sea five-degree squares averaged +13 mgals, with a maximum of +38 mgals; for 17 land squares, the average was -2 mgals, with a minimum of -5 mgals. The effect of the mean corrections of the five-degree squares on the deflections was computed in the same manner as the effect of the mean anomalies, and found to total +0″.357 on ξ and +0″.429 on η.

For the second correction, the effect of a condensation in the distant areas on the deflection is negligibly different from the effect of the original topography, so the deflection tables of DARLING [1949] may be used. The elevations were estimated for Hayford deflection compartments for that fraction of Zone 3 falling outside the local area, and for Zones 2, 1, A, and B (outer radius 10,409 km). The correction for each zone was then found by multiplying the topographic deflection due to each zone by the Hayford compensation factor F for D = 113.7 km for that zone. These corrections were found to be +0″.032 in ξ and +0″.003 in η. The total effect of the distant areas beyond about 1500 km is thus appreciably large: +0″.552 on ξ and +1″.481 on η (see Tables 2 and 3).

Discussion of errors--The two deflections which do not agree, State and Columbus, are questionable in the astronomic longitude. At State, there is an unknown personal equation in an assistant who stopped the stop watch by the chronometer; at the other three stations observed with the astrolabe, the observer stopped, as well as started, the watch. At Columbus, the observations were made by telegraphic connection with Harvard Observatory, and could be in error by $0^s.1$ or more. The neglected corrections to star places may amount to as much as $0^s.05$. If the errors at State and Columbus were due to an unknown area of gravity anomalies, it would have to be not far west or east of Columbus in order not to affect excessively the other deflection points. However, the magnitude of such a field would have to be unreasonably large; for example, if we assume a circle of ten kilometers in radius centered at 83°54′W, 40°01′N to be uniformly in error, then this error would have to be 40 mgals to produce a change in η at Columbus of 1″.52, at State of 1″.38; it would

Table 2--Gravimetrically computed deflections

Station	Item	Including field to					
		14.29 km	179.1 km	836 km	1406 km $=12.65°$	Local area $25° < \phi < 55°$ $65° < \lambda < 100°$	Whole Earth
		″	″	″	″	″	″
Conley	ξ	+0.188	+2.836	+2.560	+2.613	+2.607	+3.159
	η	+1.347	+2.712	+2.097	+1.709	+1.447	+2.918
Stanforth	ξ	-0.075	+1.371	+1.148	+1.185	+1.181	+1.737
	η	-1.126	-2.899	-3.272	-3.700	-3.962	-2.491
State	ξ	-0.583	-0.005	-0.106	-0.080	-0.082	+0.490
	η	-2.111	-5.999	-6.244	-6.702	-6.964	-5.493
Columbus	ξ	-0.718	-0.601	-0.702	-0.676	-0.678	-0.126
	η	-2.031	-6.195	-6.440	-6.898	-7.160	-5.689
Barr	ξ	+1.160	+0.271	+0.571	+0.579	+0.580	+1.132
	η	+0.901	-2.179	-2.350	-2.854	-3.116	-1.645

Table 3--Comparison of astro-geodetic and gravimetric deflections

Station	$\Delta\xi =$			$\Delta\eta =$		
	ξ_a	ξ_g	$\xi_a - \xi_g$	η_a	η_g	$\eta_a - \eta_g$
	″	″	″	″	″	″
Conley	+3.05	+3.16	-0.11	+2.25	+2.92	-0.67
Stanforth	+1.15	+1.74	-0.59	-2.55	-2.49	+0.06
State	+0.5	+0.49	+0.01	-7.8	-5.49	-2.31
Columbus	-0.07	-0.13	+0.06	-9.18	-5.69	-3.49
Barr	+1.08	+1.13	-0.05	-1.78	-1.65	-0.13

also change ξ at State 0″.38, at Columbus 0″.61, at Stanforth 0″.42, and at Barr 0″.28. But this area includes six gravity stations measured on two trips. The conclusion seems unavoidable that it is the astronomic observations and/or computations of longitude at State and Columbus which are in error.

The absolute value of g used should not differ from Potsdam system value by more than ±5 mgals. If it were in error that much, the error in ξ at Barr, the station farthest from the center of the observed field, would not be more than 0″.100. For the error in assuming the central gradient to be uniform, plus error in estimating the anomalies used to determine the gradient, the effect on the deflection should be less than 0″.03. Errors due to errors in the mean anomalies of compartments should be random, and smoothed out in the large number of compartments used.

The random error of the first corrections to the mean anomalies of the five-degree squares is estimated to average about ±2 mgals; the effect of this on the components of the deflection is about ±0″.0006. More serious is the possibility of systematic error in the first corrections; if it were of opposite sign for land squares than for sea, so that they worked in the same direction, it would be $\cos 45°$ (systematic error) $\times$ 30 $(\csc 1''/2\pi G) \times q_{avg}\,(df/d\psi)_{avg}$, or 0″.120 for an error of only 2 mgals.

The effect of the omission of the corrections to the mean anomalies of the five-degree squares not touching on the local area may safely be assumed to total less than 0″.100. The correction was computed for that square for which the effect would be largest, and found to be +4 mgals, affecting the deflection 0″.010.

The principal source of error in the gravimetric computation of the deflections is the lack of enough gravity stations to interpolate accurately, or to give an accurate mean anomaly for a given area. Several extra stations were observed as a check on values of Δg interpolated from isoanomalies in the local area, and the errors found comparable to the errors of representation given by HIRVONEN [1953].

The error in the deflection due to a summation of areal elements $\sin\psi\, d\psi\, d\alpha$ with errors of representation E_r in gravity anomaly will be

$$E_d = (\csc 1''/2\pi G)\ \sqrt{\Sigma\,[(df/d\psi)\,\sin\psi\, d\psi\, d\alpha\ E_r]^2} \quad \ldots\ldots\ldots\ldots (4)$$

For the Rice compartments, $(\csc 1''/2\pi G)\,(df/d\psi)\,\sin\psi\, d\psi\, d\alpha = 0''.001$ always. This value was extended for purposes of finding the probable error to areas where it was not actually used to compute the deflections: outward one more zone to 14°.34; inward to 100 m. Using Hirvonen's error of representation figures for given station densities are shown in Table 4.

Table 4--Probable error, local gravity field (condensed)

Zones	Radii	Station density	E_r	Number of compartments	ΣE_r^2	$0''.001\sqrt{\Sigma E_r^2}$
	km	km				″
0-29	0.1- 16.9	2- 9	0.2- 1.8	1080	591	0.024
30-41	16.9- 128.7	15- 60	3 - 6.5	432	9684	0.098
42-53	129 - 836	10- 100	2 - 9	432	30364	0.174
54-58	836 -1548	10-1000	2 -20	180	24891	0.158
0-58	0.1-1548	2-1000	0.2-20	2124	65530	±0.256

Multiplying by the sine or cosine of 45° gives the probable error of each component ξ, η as ±0″.181. Taking ±0″.30 as the probable error of the astronomic determinations, the probable error of the residuals $\Delta\xi$, $\Delta\eta$ due to the field out to 1548 km is

$$\sqrt{0.30^2 + 0.18^2} = \pm 0''.35$$

The difference of the gravimetric deflections between two stations should thus agree with the astronomic difference in deflection between the two stations with a probable error of $\sqrt{2}\,(0''.35) = \pm 0''.50$, for stations whose distance apart is small compared with the radius of the local field. Omitting the prime verticals at State and Columbus, the absolute average of the differences in this problem was 0″.31.

For the world gravity field, the mean anomalies of TANNI [1948] for five-degree squares were used. So the element of area $\sin\psi\, d\psi\, d\alpha$ is replaced by q, the area of a five-degree square

$$E_d = (\csc 1''/2\pi G)\ \sqrt{\Sigma\,[(df/d\psi)\, q\ E_r]^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

To compute an approximate value of E_d, the area from ψ = 14°.34 out to the point where $df/d\psi = 0$ was divided into three zones of about equal

$$dF = \int_{\psi_1}^{\psi_0} (df/d\psi)\,\sin\psi\, d\psi$$

and the area beyond that point into two zones of equal dF. A mean $df/d\psi$ and a mean q were assumed for each of these zones; since the mean

$$df/d\psi = \left(\int_0^{2\pi} dF\, d\alpha\right)/(\text{zone area}) = (2\pi\, dF)/(\text{zone area})$$

and the mean q = (zone area)/n, where n is the number of squares in the zone, (5) simplified to

$$E_{dz} = [(\csc 1'')/G]\ [dF/n]\ \sqrt{\Sigma E_r^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

which amounts to computing a probable error of representation for each zone

$$E_z = \sqrt{\Sigma E_r^2/n}$$

Two methods of computing the probable error were used. The first treated the mean anomalies of five-degree squares as random quantities. For the number of squares in each zone: $n = 2(\cos\psi_o - \cos\psi_i)\pi\, 2012/(4\pi)$, where ψ_o, ψ_i are the outer and inner radii of the zone, 2012 is the total number of five-degree squares. The number of squares for which anomalies are given by Tanni were counted, and his mean square errors used therefor; the rest of the squares in each zone were assumed to have a mean square error of ±30 mgals; a figure perhaps too large, since the absolute value of the mean anomaly exceeds 30 mgals for only three per cent of the five-degree squares for which values are given (see Table 5).

Table 5--Probable error, world gravity field, assumed random variation between five-degree squares

Zone	n	ΣE_r^2	E_z	dF	$(E_z dF)^2$
° °					
14.34 - 25	63	22,200	2.36	0.933	4.85
25 - 39	141	78,600	1.99	0.883	3.10
39 - 72	459	303,900	1.20	0.861	1.07
72 - 115	740	515,425	0.97	1.02	1.00
115 - 180	581	444,350	1.16	1.04	1.46
				$\Sigma(E_z dF)^2$ =	11.48

Probable error

$$E_d = 0.6745\,(\csc 1''/G)\,\sqrt{\Sigma(E_z dF)^2} = \pm 0''.483 \quad \text{.......... (7)}$$

Multiplying by the sine or cosine of 45° gives the probable error of the components ξ, η as $\pm 0''.332$. Combining this with the probable error of the local field gives the total probable error of the gravimetric deflections as

$$\sqrt{0.332^2 + 0.181^2} = \pm 0''.378$$

However, as is apparent from Tanni's map of the anomalies, there exists a correlation of the five-degree square means for distances up to 30°. So the second method used was to compute the zonal probable errors E_z from the E_r for 30° squares. For the first two zones, the gravity observations are distributed well enough so that they may be divided into 15° squares, rather than 30°. The area of each zone was computed as $A_z = 2\pi(\cos\psi_o - \cos\psi_i)$, and the number of compartments (equivalent to squares) for the purpose of computing E_z taken as $n = A_z/q$; $q = 0.0562$ for 15° squares, 0.2245 for 30° squares. For the errors of representation, the values used are expressed by the formulas

$$\text{For } 15^\circ \text{ squares: } E_r = 21 - 2S;\ S = 1, 2, \ldots, 9 \quad \text{.......... (8)}$$

$$\text{For } 30^\circ \text{ squares: } E_r = 20 - S/2;\ S = 0, 1, \ldots, 36 \quad \text{.......... (9)}$$

where S is the number of five-degree squares within the 15° or 30° square for which a mean anomaly is given. These formulas are each based on two values: for S = 9 or 36, on an assumed probable error of the mean anomaly of a five-degree square of ±10 mgals, so $E_{15} = \sqrt{9 \times 10^2}/9$, etc.; for S = 1, on the value given by HIRVONEN [1953] as the error of representation with one observation for a 15° or 30° square. The values resulting are probably a little too high (see Table 6).

$$E_d = (\csc 1''/G)\,\sqrt{58.46} = \pm 1''.61 \quad \text{.......... (10)}$$

Multiplying by the sine or cosine of 45° gives $\pm 1''.14$ for E_ξ and E_η; combining with $\pm 0''.18$ for the local gravity field gives $\pm 1''.15$ as the total probable error in ξ_g, η_g; combining with $\pm 0''.30$ for the astronomic observations gives $\pm 1''.19$ as the total probable error in $\Delta\xi$, $\Delta\eta$.

Conclusions and summary--Considering the probable errors due to the distant areas, the good agreement obtained between the astronomic and gravimetric deflections is probably due to chance. The outstanding difference from the investigation of RICE [1952] is that the best agreement was not attained until the sizeable effect of anomalies well beyond 1500 km was included. Various conclusions which may be drawn: (1) The gravimetric method of computing deflections will not be precise

Table 6--Probable error, world gravity field, assumed random variation between 30° squares

Zone	Size of square	n	ΣE_r^2	E_z	dF	E_{dz}	$(E_z dF)^2$
° °	°					″	
14.34 - 25	15	7	399	2.86	0.933	0.56	7.11
25 - 39	15	16	2350	3.03	0.883	0.56	7.20
39 - 72	30	13	3130	4.29	0.861	0.78	13.65
72 -115	30	21	4833	3.31	1.02	0.71	11.41
115 -180	30	16	4617	4.20	1.04	0.92	19.09
							$\Sigma(E_z dF)^2 = 58.46$

enough for geodetic use until a world gravity survey is accomplished with station spacing of ten degrees or closer. (2) For the local area, gravity stations closer together than four kilometers are not worthwhile. Ideal seems a general net with stations ten kilometers apart, plus about six extra stations within ten kilometers of the deflection point. (3) The density of the gravity net required for the local area would cause considerable work in undeveloped areas, in travel, and in horizontal and vertical location. (4) Of the possible uses of gravimetric deflections, one purpose for which they are not the best method is obtaining the deflection in order to compute corrections to azimuths by $\Delta\alpha = \zeta \tan \beta$, where ζ is the deflection in a plane at right angles to the azimuth, and β is the angle of inclination of the line of sight. The gravimetric method is most difficult to compute just where this correction is required, namely, in mountains. (5) Different types of anomalies may be used in different areas for gravimetric computation of deflections, but the labor of making the necessary corrections should be carefully weighed against the advantages gained thereby.

Further research is needed in: (1) Comparison of gravimetric and astronomic deflections in an area of extreme topography and gravity variation, such as the West Indies or the California mountain ranges, with analysis of various methods of reduction. (2) Comparison of gravimetric and astronomic deflections at several points distributed at intervals of, say, 1000 mi all over North America, as a means of evaluating the variation in the systematic error due to distant areas of unknown anomaly. Such a project might even be used to predict the anomalies in areas of presently unknown anomaly. It would also be useful in more accurately fixing the datum. (3) Further analysis of the problem of error of representation of one or a few gravity anomalies for a given area, and of the extent of correlation of anomaly differences with spacing. (4) Comparison of various methods of treating gravity data with a view to smoothness of variation of the gravity anomaly from place to place. (5) Analysis of the corrections required when using different type anomalies in different areas, and development of methods of applying the corrections.

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AEROMAGNETIC SURVEYS IN THE ALEUTIAN, MARSHALL, AND BERMUDA ISLANDS

Fred Keller, Jr., J. L. Meuschke, and L. R. Alldredge

(Publication authorized by the Director, U. S. Geological Survey)

Abstract--Total-intensity aeromagnetic surveys of the Aleutian, Marshall, and Bermuda Islands were completed in 1948. The anomalies associated with the Aleutian volcanoes are attributed mainly to topographic relief and are not an indication of the degree of volcanic activity. Eniwetok presents a magnetic pattern that would be produced by an irregular-shaped rimmed depression in the basement, modified by the two adjoining seamounts, and differs from Bikini, whose magnetic features would be produced by a broad seamount with irregular surface relief. The Bermuda survey demonstrated magnetic features typical of volcanic rocks. Comparison of an observed and a theoretical profile computed by Press and Ewing indicates that their assumptions are reasonably correct. The Aleutian Trench survey shows anomalies that are attributed to susceptibility contrasts but none that can be correlated with the trench. A traverse from Adak, Aleutian Islands, to Kwajalein, Marshall Islands, exhibited several large anomalies that are presumed to be caused by susceptibility contrasts but may be indications of uncharted seamounts. Two traverses, one from Cape May, N. J., to Bermuda and the other from Bermuda to Long Island, N. Y., reveal a change in the magnetic field approximately 300 miles from the Atlantic Coast that indicates a possible thinning of the sial and an exposure of sima.

Introduction--As part of its program of Aleutian Volcano Investigations, the U. S. Geological Survey in cooperation with the Office of Naval Research conducted total-intensity aeromagnetic surveys during the summer of 1947 to investigate the possibility of determining the future activity of Aleutian volcanoes by aeromagnetic methods. Designated Project Volcano by the Office of Naval Research, this project included also surveys over several atolls in order to compare magnetic features of atolls with those of known volcanoes. Several ocean traverses incidental to these main projects were flown.

The project encompassed the following:

(1) Three volcanoes in the Aleutian Islands, on Adak, Great Sitkin, and Umnak.
(2) Atolls of Bikini and Eniwetok, Marshall Islands.
(3) Eight traverses over Bermuda and the surrounding area.
(4) Eight traverses across the Aleutian Trench.
(5) A traverse from Adak, Alaska, to Kwajalein, Marshall Islands, via Midway and Wake Islands.
(6) Two traverses across the northeastern Atlantic Continental Shelf.

This report is presented as a brief summary of the more interesting features of the investigations. It is planned that some of the data will be published in conjunction with more comprehensive reports on single geologic provinces.

The areas surveyed in the Aleutian Islands were chosen to provide a comparison between inactive volcanoes such as Mount Moffet on Adak and active ones such as Great Sitkin and Okmok on Umnak.

Aeromagnetic survey of Great Sitkin, Alaska--Great Sitkin [SIMONS and MATHEWSON, 1947] is one of the Andreanof Islands near the middle of the Aleutian arc; it lies about 25 mi (40 km) northeast of Adak. The island is about 11 mi (18 km) in diameter and rises to an altitude of 5740 ft (1750 m). The northern half of the island is an active volcano, and the southern half is a dissected remnant of an extinct volcano. Volcanic activity is reported to have occurred on Great Sitkin in 1792, 1829, 1904, 1933, and 1945, the most recent activity resulting in the formation of a basalt crater dome in March, 1945.

Nine continuous profiles were made showing the variation of total magnetic intensity at an altitude of 7500 ft (2.3 km) over the Great Sitkin volcano. The profiles were adjusted by means of base-line traverses flown on the north and south sides of the island. Total intensity contours were drawn with an interval of 50 gammas. A smaller contour interval was not possible because the location of the aircraft with respect to the ground was not sufficiently well known.

The aeromagnetic map (Fig. 1) shows an anomaly of approximately 600 gammas, which conforms in general with the topography of the volcanic cone. The basalt dome, which was extruded in 1945, and which was still glowing and smoking in 1947, had little or no effect on the magnetic field. There were no negative anomalies present to indicate a reduction of susceptibility where the dome rocks were hot.

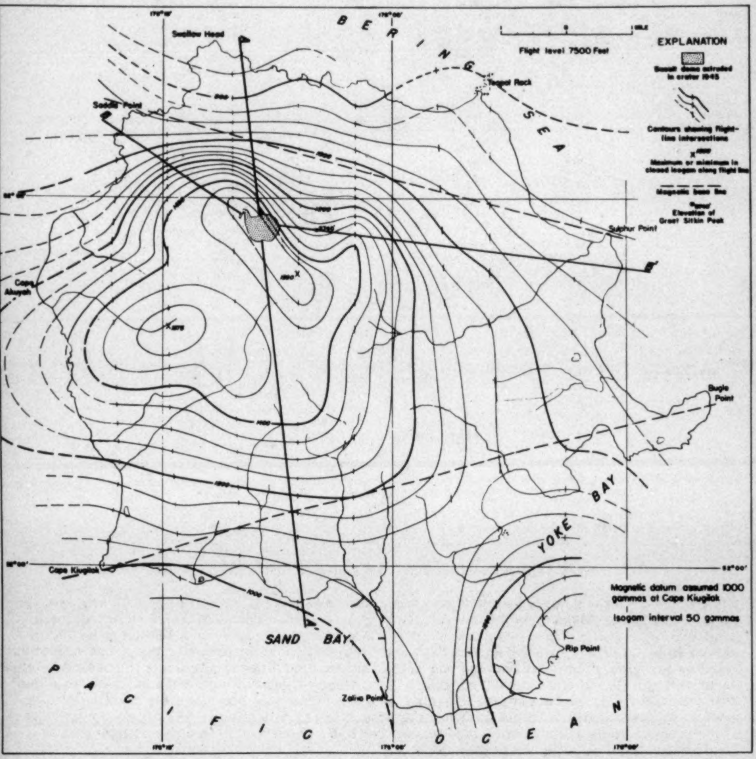

BERING SEA
Swallow Head
Saddle Point
Tanaga Rock
Flight level 7500 Feet
EXPLANATION
Basalt dome extruded in crater 1945
Contours showing flight-line intersections
Maximum or minimum in closed isogam along flight line
Magnetic base line
Elevation of Great Sitkin Peak
Sulphur Point
Cape Aluyah
Bugle Point
YOKE BAY
Cape Kiugilak
52°00'
Magnetic datum assumed 1000 gammas at Cape Kiugilak
Isogam interval 50 gammas
SAND BAY
Rip Point
Zaliva Point
PACIFIC OCEAN

Fig. 1--Aeromagnetic map, uncorrected for regional gradient, of Great Sitkin, Alaska

To help bring into greater prominence, changes in the magnetic gradient that were not apparent on the original map, a second vertical derivative map was made [HENDERSON and ZIETZ, 1949].

In the second vertical derivative map of Great Sitkin (Fig. 2) the anomaly conforming with the topography of the island has been essentially removed and the anomaly over the basalt dome has been accentuated.

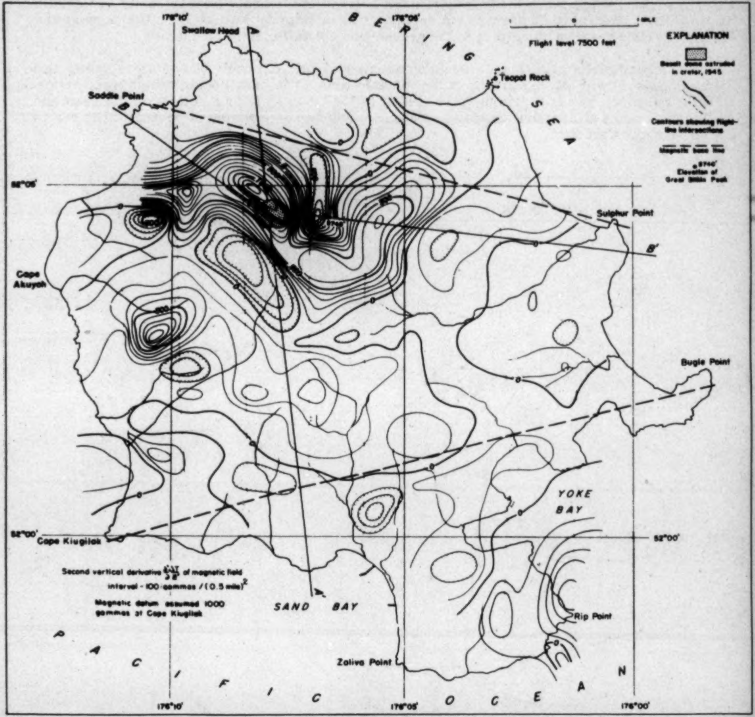

176°10'
176°05'
176°00'
52°05'
52°00'
B E R I N G S E A
P A C I F I C O C E A N
Swallow Head
Teapot Rock
Saddle Point
Sulphur Point
Cape Akuyah
Bugle Point
Cape Kiugilak
YOKE BAY
SAND BAY
Rip Point
Zaliva Point
B
B'
N
1 MILE
Flight level 7500 feet
EXPLANATION
Basalt dome extruded in crater, 1945
Contours showing flight-line intersections
Magnetic base line
5740'
Elevation of Great Sitkin Peak
Second vertical derivative $\frac{\partial^2 \Delta T}{\partial z^2}$ of magnetic field
interval - 100 gammas / (0.5 mile)^2
Magnetic datum assumed 1000 gammas at Cape Kiugilak

Fig. 2--Second vertical-derivative map of Great Sitkin, Alaska

Geologic sections across Great Sitkin along lines AA' and BB' of Figure 2 and a geologic section across Mount Adagdak on Adak along CC' of Figure 3 are shown together with the magnetic profile along the same lines in Figure 4. Three magnetic profiles for each section show the observed field, profile A, which includes the Earth's normal field, the anomaly due to the magnetic mass or topography, and the anomaly due to the polarization of the basalt dome; the second vertical derivative, profile B; and a smoothed profile C, obtained by subtracting a residual field from the observed field. The smoothed profile C may be better correlated than the other profiles with the general topography of the island, although the peak of the profile is no longer over the highest part of the island. The second vertical derivative, profile B, which is plotted on an exaggerated scale, clearly shows the basalt dome in the crater.

The correlation of the observed magnetic profile A and the smoothed profile C with topography can readily be seen in profile BB' of Great Sitkin. However, there has been an increase of definition in the second vertical derivative profile, and the presence of a plug close to the crater dome is indicated by the double peak. The plug to the east of the crater dome was mapped on doubtful evidence and may not actually be located there. The sharp negative in the magnetic profile may be caused by the sharp topographic features formed by the peak of the volcano. The scales of the second vertical derivative profiles are exaggerated.

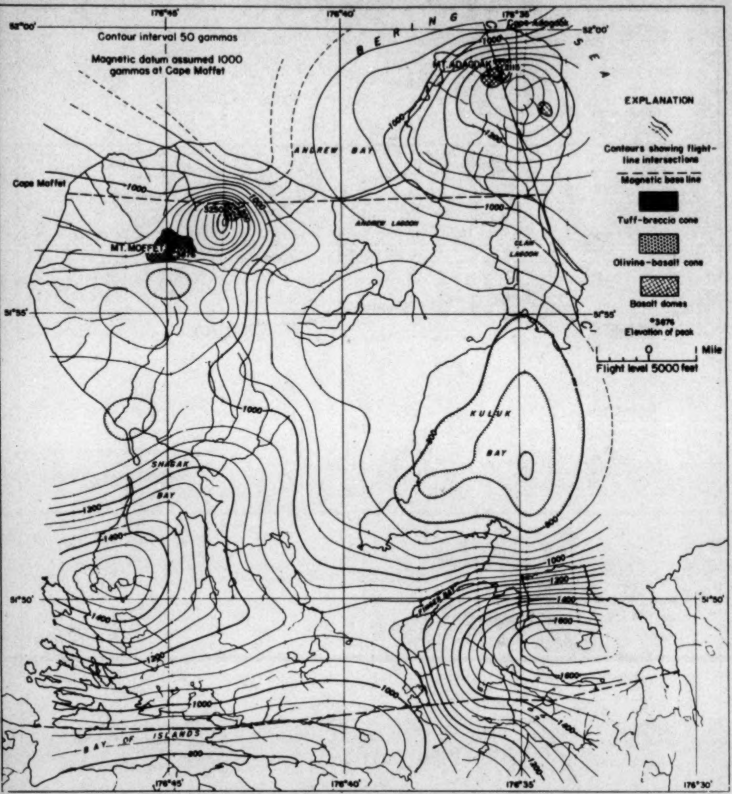

Contour interval 50 gammas
Magnetic datum assumed 1000 gammas at Cape Moffet
176°45'
176°40'
176°35'
176°30'
52°00'
51°55'
51°50'
BERING SEA
Cape Adagdak
MT. ADAGDAK
ANDREW BAY
ANDREW LAGOON
CLAM LAGOON
Cape Moffet
MT. MOFFET
KULUK BAY
SHAGAK BAY
FINGER BAY
BAY OF ISLANDS
1000
1200
1400
1600
1800
800
EXPLANATION
Contours showing flight-line intersections
Magnetic base line
Tuff-breccia cone
Olivine-basalt cone
Basalt domes
Elevation of peak
1 0 1 Mile
Flight level 5000 feet

Fig. 3--Aeromagnetic map, uncorrected for regional gradient, of northern Adak, Alaska

Aeromagnetic survey of Adak, Alaska--An aeromagnetic map of northern Adak was made to obtain a comparison between the anomalies over a quiescent volcano such as Adak and those over an active volcano such as Great Sitkin. Adak with an area of more than 200 sq mi is the largest of the Andreanof group of the Aleutian Islands. The southern part of the island consists of folded, faulted, and altered Mesozoic volcanic rocks intruded by gabbro. The northern mountainous part [COATS, 1947] consists of remnants of three Tertiary basaltic volcanoes that are believed to have been inactive since early Quarternary time.

The aeromagnetic survey of northern Adak was flown at an elevation of 5000 ft (1.5 km) above sea level with a flight-line spacing of one mile (1.6 km). The average elevation above the ground was greater for Great Sitkin than for Adak. The anomalies over Adak (Fig. 3) range from 400 to 700 gammas, whereas the anomaly over Great Sitkin is about 600 gammas.

An anomaly of approximately 700 gammas is associated with the large mass of gabbro that crops out south of Finger Bay. The second derivative map (Fig. 5) of the same area indicates that

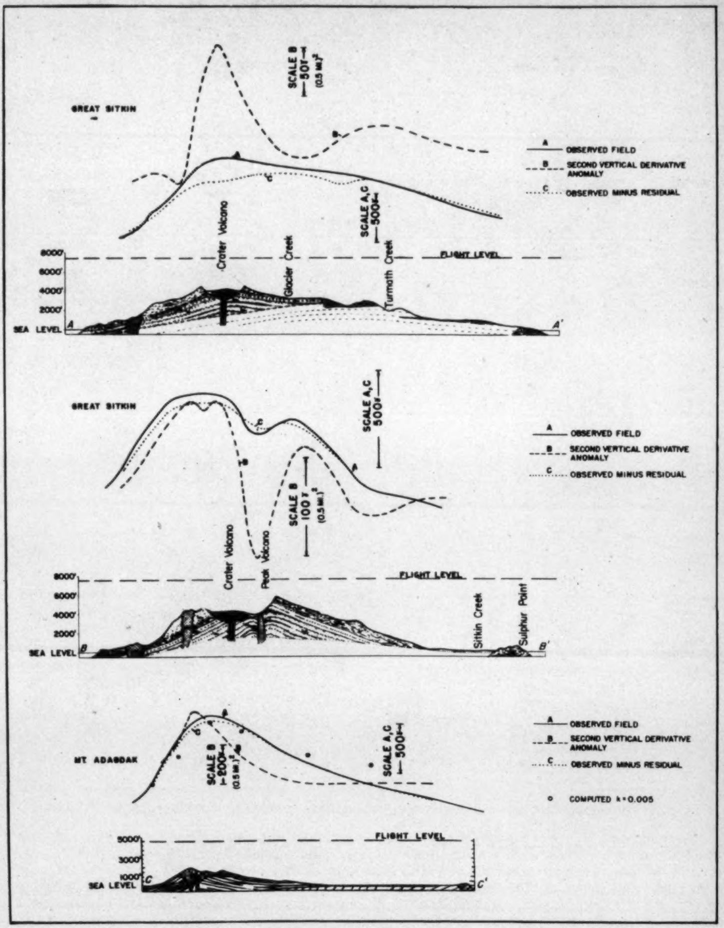


Fig. 4--Magnetic anomalies over Aleutian volcanoes

this intrusive mass probably has greater lateral dimensions than are shown on the surface. This is demonstrated by the double character of the anomaly and the configuration of the zero curvature line. In a recent publication, VACQUIER, STEENLAND, HENDERSON, and ZIETZ [1951] have shown that the zero curvature line roughly outlines the edges of vertical prisms polarized by induction in the Earth's magnetic field.

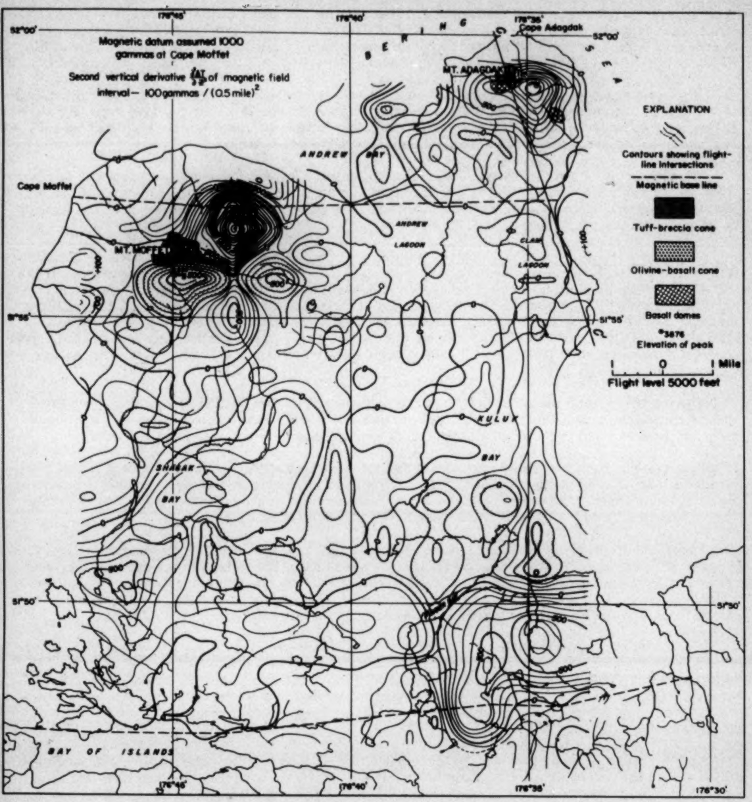

Magnetic datum assumed 1000 gammas at Cape Moffet
Second vertical derivative $\frac{\partial^2 \Delta T}{\partial z^2}$ of magnetic field
interval— 100 gammas / (0.5 mile)^2
EXPLANATION
Contours showing flight-line intersections
Magnetic base line
Tuff-breccia cone
Olivine-basalt cone
Basalt domes
*3876 Elevation of peak
1 0 1 Mile
Flight level 5000 feet
Cape Moffet
MT. MOFFET
MT. ADAGDAK
Cape Adagdak
BERING SEA
ANDREW BAY
ANDREW LAGOON
CLAM LAGOON
KULUK BAY
SHAGAK BAY
BAY OF ISLANDS
176°45'
176°40'
176°35'
176°30'
52°00'
51°55'
51°50'

Fig. 5--Aeromagnetic map of northern Adak, Alaska

The anomalies associated with the basalt domes on Mount Adagdak and the composite parasitic olivine-basalt cone on the northeastern flank of Mount Moffet are clearly indicated on both the original and the second-derivative map. The tuff-breccia cone and its basaltic ventfilling at the site of the present summit of Mount Moffet is shown to a lesser degree by an extension of the contours from the anomaly associated with the parasitic cone. The different cones are shown to much better advantage by the second-derivative map than by the observed anomalies. The large anomaly shown at the southwestern corner of the surveyed area is in a region in which the geology has not been mapped; however, the appearance of this anomaly suggests a gabbro intrusive similar to the intrusion south of Finger Bay.

In Figure 4 the profile CC′ over Mount Adagdak shows the peaks of the smoothed and observed magnetic profiles offset from the peak of the volcano; the second vertical derivative anomaly is almost centered over the plug that forms the peak. Values of the magnetic field computed to match the observed profile A of Mount Adagdak are indicated by the small circles plotted with the profiles. It was found that by using the topographic profile CC′ and the flight level of 5000 ft a susceptibility contrast of 0.005 cgs was necessary to give an approximate fit with the observed profile. This value of 0.005 cgs is a reasonable figure for the susceptibility of a basaltic mass such as this.

The magnetic low over Kuluk Bay has been postulated by some to indicate a greater thickness of sediments than was previously thought to exist. However, this low is not entirely structural. It is a well-known characteristic in northern magnetic latitudes for a magnetic high such as the one shown to the south to exhibit a well-defined low on its north flank.

A comparison of the anomalies associated with Great Sitkin and those associated with northern Adak do not show any striking difference that could be attributed to the state of activity of their respective volcanoes. The degree of smoothness and the amplitude of the magnetic profiles seem to be of the same order of magnitude.

Aeromagnetic survey of part of northeastern Umnak, Alaska--Umnak [BYERS, HOPKINS, WIER, and FISHER, 1947] is a dumbbell-shaped island, 70 mi (113 km) long, in the eastern part of the Aleutian Islands. A large broad volcanic mountain, Okmok Volcano, comprises the central northeastern part of the island. The central part of the volcano is Okmok caldera, a large cliff-rimmed depression 7 1/2 mi (12 km) in maximum diameter, with cliffs which range in altitude from 1500 to 2500 ft (0.46 to 0.76 km) above the caldera floor. The caldera contains nine large cinder cones and many smaller ones, some of which were emitting steam and smoke during the magnetic survey in July, 1947.

Twenty-three north-south aeromagnetic traverses were flown 6500 ft (2 km) above sea level across the northeastern part of Umnak. These profiles were spaced one mile (1.6 km) apart and were adjusted to base lines flown along the northern and southeastern shores of the island.

The caldera rim is outlined approximately by the pattern of the magnetic contours on the aeromagnetic map of northeastern Umnak (Fig. 6). There is no magnetic evidence, however, of any of the nine large cones, but there is a large anomaly associated with the central part of the caldera. This may be caused by a susceptibility contrast of the underlying rocks.

Mount Tulik, on the southeastern flank of Okmok Volcano, is marked by an anomaly of approximately 700 gammas. Mount Tulik has an altitude of 4111 ft (1253 m) and is composed entirely of basalt. The difference in altitude between this peak and the surrounding terrain probably accounts for the sharp anomaly. In the vicinity of Mount Idak the basalt flows seem to be expressed by a general increase in magnetic intensity from northeast to southwest.

There are no negative anomalies in this area that can be attributed to large masses of rock at temperatures greater than the Curie point. Most of the anomalies obtained seem to be related to the topographic configuration of the magnetic basalts, with the exceptions of the anomaly on the northern flank of Okmok Volcano and the anomaly associated with the center of the caldera. Otherwise there is apparently little variation in the mineral composition or magnetic susceptibility of the rocks.

Aeromagnetic survey of Eniwetok, Marshall Islands--Data for the aeromagnetic map of Eniwetok, a coral atoll in the Marshall Islands (Fig. 7), were obtained by flying ten east-west and ten north-south magnetic profiles across the atoll. The traverses were flown with a spacing of two miles (3.2 km) at an altitude of 1500 ft (0.46 km). The only ground points available for checking the location of the airplane were points on the few islands and the coral reefs on the flight path. The location of points on the reefs was inexact, and consequently the locations of the profiles within the atoll are not precise; but the magnetic values on the two profiles at flight-line intersections all agreed within 50 gammas. Traverses were extended beyond the limits of the atoll by using the ground speed observed while crossing the lagoon and extrapolating the direction and distance flown beyond the coral reef before turning.

The assumption that the coral atoll is underlain by an old basaltic volcanic cone may be justified by considering the aeromagnetic map. It can be shown that at low magnetic latitudes the topography of a rock mass that is uniformly magnetized in the Earth's field is expressed by a magnetic low at the crest and a magnetic high at the depression [VESTINE and DAVIDS, 1945]. This is the situation at Eniwetok. The aeromagnetic map suggests that the crater of the underlying volcano is approximately under the center of the lagoon and the rim or edge at the ring of magnetic lows around the periphery of the atoll. Comparing this situation with that at Okmok caldera on northeastern Umnak, the magnetic picture is reversed, as it should be. At Umnak, where the magnetic

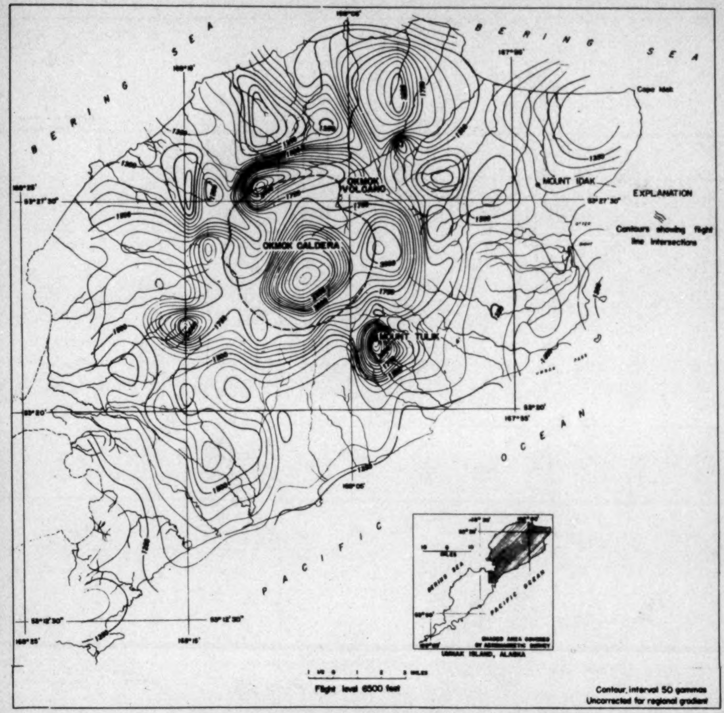

BERING SEA
BERING SEA
Cape Idak
OKMOK VOLCANO
MOUNT IDAK
EXPLANATION
Contours showing flight line intersections
OKMOK CALDERA
MOUNT TULIK
PACIFIC OCEAN
BERING SEA
PACIFIC OCEAN
SHADED AREA COVERED BY AEROMAGNETIC SURVEY
UMNAK ISLAND, ALASKA
Flight level 6500 feet
Contour interval 50 gammas
Uncorrected for regional gradient

Fig. 6--Aeromagnetic map of part of northeastern Umnak, Alaska

field is essentially vertical, the caldera rim is indicated by a ring of sharp magnetic highs; however, a central magnetic high presumably caused by a susceptibility contrast confuses the simple picture.

The northwest trend of the anomalies is probably caused by two guyots, submerged flat-topped peaks, that occur at the northwestern and southeastern edges of the atoll. The outer edges of the atoll seem to rest on part of the flat surfaces of the guyots [HESS, 1948].

As part of Project Volcano a survey was made of Bikini atoll; the results were published in a separate paper by ALLDREDGE and KELLER [1949]. The magnetic map of Bikini showed a few minor positive peaks within a broad negative anomaly. An anomaly of this type would be produced by a broad seamount with irregular surface features in the basement. The observed total-intensity field was duplicated by ALLDREDGE and DICHTEL [1949] by using a miniature flux-gate type detector to measure a magnetic model.

Aeromagnetic survey of the Bermuda Islands--During the spring of 1948, six aeromagnetic traverses were flown across the Bermuda Islands at an altitude of 1000 ft (0.3 km). The locations of the traverses, plotted magnetic profiles, and bottom profiles are shown in Figure 8.

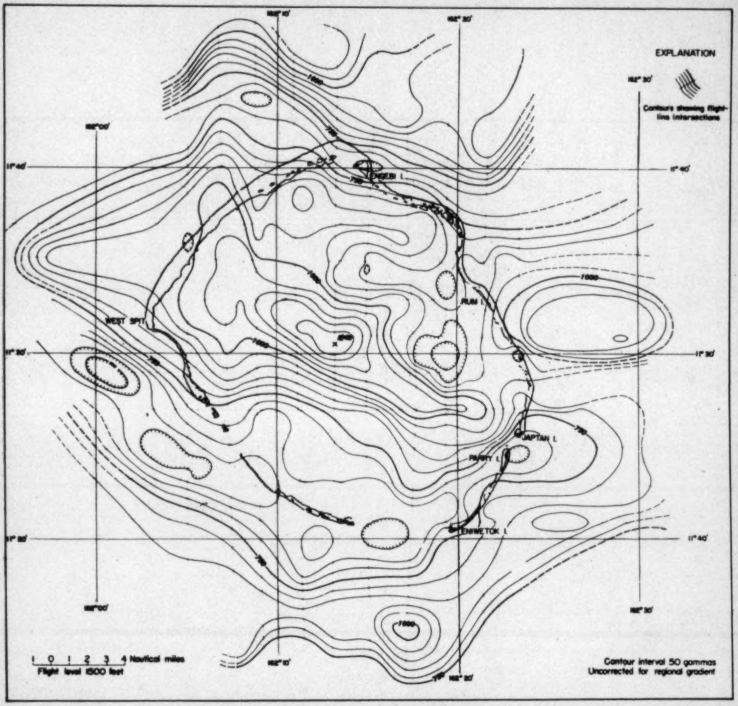
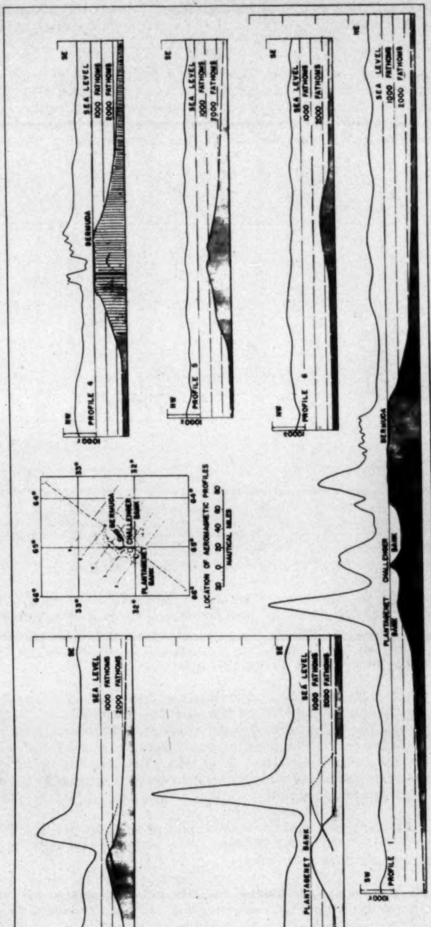

162°10'
162°20'
EXPLANATION
162°30'
Contours showing flight-line intersections
162°00'
11°40'
11°40'
ENGEBI I.
RUNIT I.
WEST SPIT
11°30'
11°30'
JAPTAN I.
PARRY I.
ENIWETOK I.
11°20'
11°40'
162°00'
162°30'
1000
750
1 0 1 2 3 4 Nautical miles
Flight level 1500 feet
162°10'
162°20'
Contour interval 50 gammas
Uncorrected for regional gradient

Fig. 7--Aeromagnetic map of Eniwetok, Marshall Islands

According to VERRILL [1907] the Bermuda Islands are a pseudatoll, with the islands resting on the eroded summit of a volcano that was formed during or at the end of the Triassic. The underlying rocks of Bermuda are very magnetic; the magnetic declination around Bermuda varies as much as six degrees. Two smaller but relatively sharp underwater features, Challenger Bank and Plantagenet Bank, are located on the southwestern side of the Bermuda Islands. The overall structure of the pseudatoll is elliptical, with the longest axis running northeast.

Profile 1 (Fig. 8) was flown along the northeastern axis of Bermuda, with the line extending seaward approximately 80 mi (130 km). This profile shows anomalies ranging from 1000 to 1500 gammas over Bermuda and Challenger Bank, and a 3000-gamma anomaly near Plantagenet Bank. The high amplitude of the anomalies indicates that the area is underlain by volcanic rocks, probably basaltic in composition. The other five profiles were flown at right angles to the main axis of Bermuda.

The displacement of the anomalies from Challenger Bank and Plantagenet Bank shown in profiles 2 and 3 may be explained by navigational errors. The dashed line shows the relative position of the banks with respect to the magnetic profiles.



Average flight level 1000 feet

Profiles corrected for gradient of earth's main magnetic field

Fig. 8--Aeromagnetic profiles across the Bermuda Islands

The anomaly over Plantagenet Bank, profile 2, is 5000 gammas. This is unusually large for a volcanic feature unless there is also a high concentration of some magnetic mineral, such as magnetite.

Profile 4 has been plotted on a larger scale (Fig. 9) because it is the result of observed data over the same line that was computed on theoretical assumptions by PRESS and EWING [1952]. The profile was computed assuming a truncated cone of basaltic rock with a magnetic susceptibility of 0.01 cgs and a relief equal to that of Bermuda above the ocean bottom. The magnetization was assumed to consist only of induced magnetization from the Earth's magnetic field. The similarity between the observed and the computed profile is remarkable and indicates the validity of the original assumption. Although the observed and computed profiles do not agree in detail directly over Bermuda, they are similar as to the value of the high on the southeastern side and in the configuration of the anomaly on both sides of Bermuda, especially with regard to the magnetic low which increases in intensity seaward in the northwestern part of the profile.

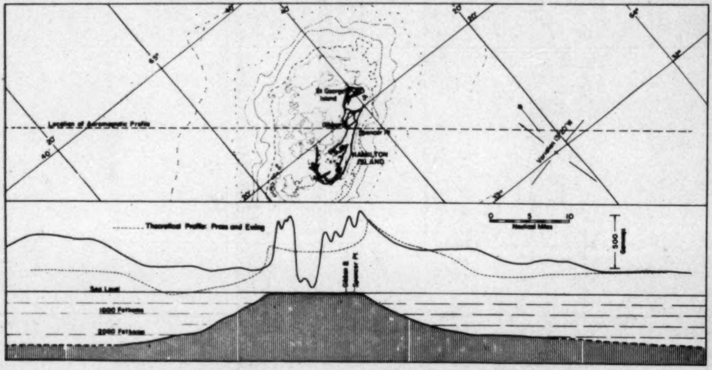


Fig. 9--Northwest-southeast profile across Bermuda Islands

Aleutian Trench traverses--Eight aeromagnetic traverses were flown mainly at an altitude of 500 ft (152 m), southward from the Aleutian Islands for an average distance of 200 mi (322 km) across the axis of the Aleutian Trench. Both the aeromagnetic profiles and the bottom profiles (Fig. 10) have been plotted. The data for the bottom profiles were taken from published soundings on the U. S. Coast and Geodetic Survey navigation charts. In general, the sounding coverage in the area of the Aleutian Islands is excellent, and adequate topographic detail is present to permit close comparison between bottom configuration and magnetic profiles.

The regional gradient has been removed from the aeromagnetic profiles by plotting values of the Earth's normal total intensity field [VESTINE and Others, 1947] along the magnetic traverse and subtracting the normal value from the observed value.

The eight magnetic profiles have no consistent anomalies that can be correlated with the Aleutian Trench. The intensity of the measured anomalies indicates that they are produced by susceptibility contrast within the rocks of the sea floor rather than by the topography of their surface. The lack of correlation between the anomalies and the trench indicates that the structures which produced the susceptibility contrasts have no relation to the trench and that any structures related to it did not produce recognizable susceptibility contrasts.

The large negative anomaly of approximately 1000 gammas in profile 1 (Fig. 10) occurs in the region of the Patton Seamount. This seamount is at the northwestern end of a curving range of submarine mountains that consists of parallel ridges in this area. Harold Murray of the U. S. Coast

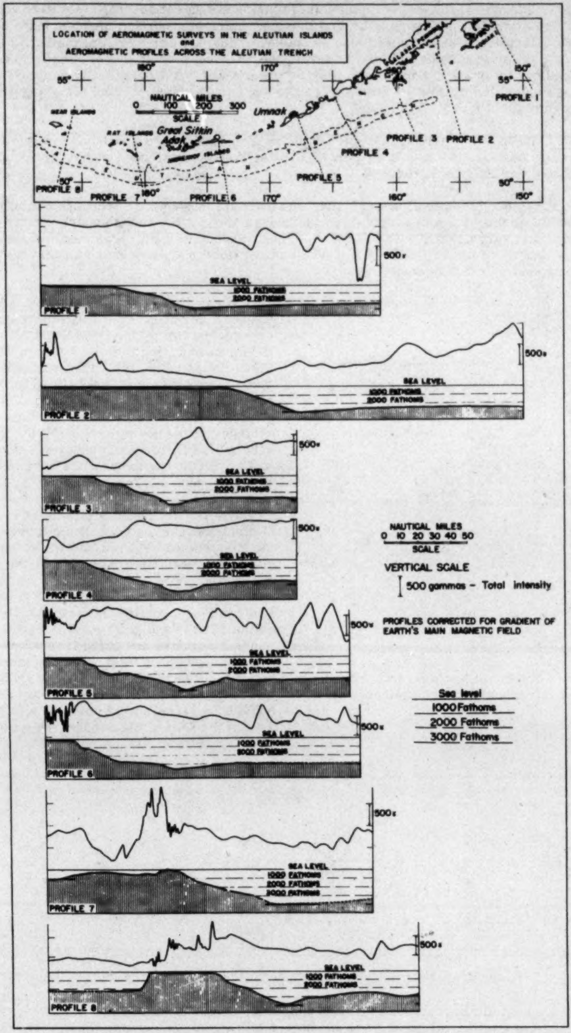


Fig. 10--Aeromagnetic profiles across the Aleutian Trench and Geodetic Survey expressed the opinion (personal communication) that a negative anomaly in this area would indicate the possibility that these submarine mountains are composed of sialic rocks. This negative anomaly could also be caused by inverse remanent magnetization or by a deep narrow valley in the ocean floor; however, the most reasonable assumption is that the traverse passed over a granitic body in the basaltic ocean floor. A susceptibility contrast on the order of 0.007 cgs units, the difference between granite and basalt, could account for a negative anomaly of this magnitude.

Adak, Alaska, to Kwajalein, Marshall Islands--The results of a continuous magnetic traverse made between Adak and Kwajalein as part of Project Volcano have been previously published [ALLDREDGE and KELLER, 1949].

A large number of anomalies were observed over areas shown by hydrographic charts to be at least 3000 fathoms (5.5 km) deep, which would indicate that the rocks underlying the ocean floor are complex and vary greatly with regard to magnetic susceptibility. It is possible, however, in view of the paucity of ocean-depth data, that the ocean floor may have more topographic relief than has been mapped by existing soundings.

Aeromagnetic traverses from the Atlantic Coast to Bermuda--Two Atlantic magnetic traverses were flown, one from Cape May, N. J., to Bermuda and the other from Bermuda to Long Island, N. Y. (Fig. 11). The eastward flight was made at an altitude of 500 ft (0.15 km) and the return flight at 1500 ft (0.46 km). The regional gradient has been removed from the profiles by subtracting the normal value [VESTINE and Others, 1947] from the observed value. The resulting aeromagnetic profiles have been plotted with the ocean-bottom profiles (Fig. 12).

The aeromagnetic profiles show a small but distinct anomaly on each of the traverses near the eastern edge of the Continental Shelf. The anomalies begin approximately at the shelf edge and extend shoreward about 25 nautical miles, reaching a peak near the 40-fathom line on the Ludlam Beach profile and near the 50-fathom line on the Fire Island profile. The depth measurements mentioned are taken from Coast and Geodetic Survey chart 1000. These anomalies, when the difference in altitude of the airplane is considered, are similar to the anomaly described by AFFLECK [1948] in his analysis of a profile across the Gulf of Mexico and the western part of the Caribbean Sea.

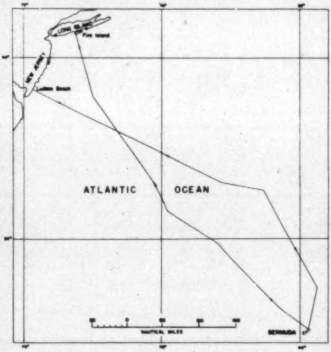


Fig. 11--Location of aeromagnetic profiles from the Atlantic Coast to Bermuda

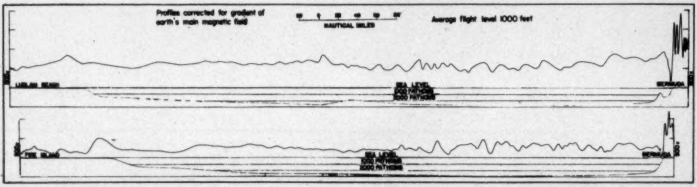


Fig. 12--Aeromagnetic profiles, Cape May to Bermuda and Bermuda to Long Island

Computations indicate that the magnetic anomalies cannot be attributed to the "edge effect" of a thick plate of continental sialic rock in contact with a plate of oceanic simatic rock. The most likely explanation is that these anomalies are caused by a mass, possibly intrusive, at least 30 mi

(48 km) wide that parallels the edge of the continent. The computed depth to the top of this mass agrees with the recent findings of EWING and Others [1950], who show the basement in this area to be from 12,000 to 16,000 ft (3.6 to 4.9 km) beneath the surface.

A small magnetic low followed by a small high occurs on both profiles approximately 70 mi (110 km) seaward from the Continental Shelf and the anomalies associated with it. This anomaly is east of the Continental Shelf by approximately the distance at which the gravity surveys of Vening Meinesz [UMBGROVE, 1947] generally show an increase in the isostatic anomalies.

The marked changes in both profiles, approximately 300 mi (480 km) seaward, from a smooth magnetic field on the west to one on the east that is relatively more complex, may indicate a major discontinuity between a relatively thick sialic layer to the west and a relatively thin one to the east. The remainder of the profile to Bermuda in each traverse shows anomalies that are similar to portions of the profile over the Pacific Ocean from Adak to Kwajalein. This may indicate an absence of the sial from this area.

Conclusions--The project included so many and such varied types of aeromagnetic surveys that it has been impossible to give the analysis of the data from each survey the detailed attention that it should have. The following conclusions, however, may be drawn from the information obtained.

Almost all of the anomalies associated with Aleutian volcanoes seem to be caused by the topographic configuration of the volcanoes. No negative anomalies were found that could be attributed to a mass of rock with temperatures above the Curie point.

The magnetic features of Eniwetok are a broad magnetic high area centered over the lagoon with a series of lows around the periphery of reef and another high area seaward that is modified by the guyots adjacent to the northwestern and southeastern edges of the atoll. This pattern would be produced by an irregular-shaped cone with a rimmed depression in its center. The anomalies associated with Bikini differ from those of Eniwetok, for Bikini shows a broad negative anomaly with a few minor positive peaks. An anomaly with such magnetic features would be produced by a broad seamount with irregular surface relief.

The Bermuda survey shows in general a correlation between the topography and the magnetic pattern. The large anomaly over Plantagenet Bank may indicate a high concentration of magnetite. The agreement between the observed profile and the theoretical profile computed by PRESS and EWING [1952] indicates that their assumptions and method are reasonably correct.

The magnetic profiles of the Aleutian Trench show anomalies that are attributed to susceptibility contrasts but none that can be correlated with the trench.

The traverse from Adak to Kwajalein demonstrated the feasibility of making reasonably accurate long-range surveys with the airborne magnetometer. Some relatively large anomalies were found over deep areas that are presumed to be caused by susceptibility contrasts but may be caused by bottom topography such as uncharted seamounts.

There is a magnetic anomaly associated with the Continental Shelf which seems to originate from a large deep mass, possibly intrusive, that is approximately parallel to the continent. There may be a correlation between the small magnetic anomaly that occurs on both profiles about 70 mi (112 km) seaward from the Continental Shelf and the gravity anomalies that are found approximately the same distance seaward by various surveys of Vening Meinesz. The change in the profile from a relatively smooth magnetic field to a more complex one approximately 300 mi (480 km) from the Atlantic shore may indicate a thinning of the sial and possibly the exposure of the sima at the ocean bottom.

Acknowledgments--The aeromagnetic surveys were sponsored by the Office of Naval Research. The Naval Ordnance Laboratory participated by assigning personnel to install and maintain the Naval Ordnance Laboratory - Bell Telephone Laboratories AN/ASQ-3A airborne magnetometer, which had been modified for geophysical use.

All survey flights were made in a Navy PBY-5A airplane that was commanded by E. M. Ward from the Naval Aircraft Modification Unit, Johnsville, Pennsylvania.

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SUBSURFACE DENSITY INVERSIONS OFF NANTUCKET ISLAND

Albert Ehrlich

Abstract--Stations occupied south of Nantucket Island in the region of the discontinuity between the outflow waters of the Gulf of Maine and the denser offshore water show density inversions in the middle levels. The inversions are correlated with the tidal period, but not with the diurnal period. Rayleigh's instability criteria and other methods are used to investigate the conditions under which such inversions can exist. An equation is derived to obtain current velocities at different levels throughout the tidal period, from the surface tidal currents. Trajectories for each level indicate extensive overrunning of the lower layers by the upper layers during each tidal period. The magnitude of this overrunning is sufficient to reverse the slope of the discontinuity surface between the Gulf of Maine waters and the offshore waters, and to cause the inversions observed. A comparison between the conditions off Nantucket Island and cases of instability in other parts of the Atlantic Ocean shows a basic dissimilarity between them.

Introduction--It has been shown previously [SPILHAUS, EHRLICH, and MILLER, 1950] that subsurface density inversions exist over the edge of the continental shelf south of Nantucket Island, and that these inversions are correlated with the tidal, but not with the diurnal, period. Altogether over 25 stations in the area show these inversions (Fig. 1). This paper is an extension of the investigation of conditions under which the inversions are found, and an attempt to determine the cause of the inversions.

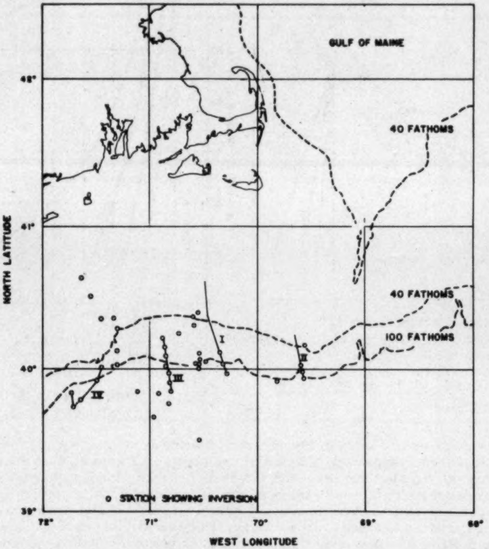

Fig. 1--Stations with inversions in the Nantucket area

Probabilities of inversions appearing at a station--The stations showing inversions, however, represented only about 15 pct of the total number of stations occupied in the area. If the inversions are real and present, why did not more of the stations indicate them? This could be due to any one of three reasons. (1) The inversions are not present all the time. (2) Several of the stations do not extend down as far as the level of the inversions. (3) An oceanographic station is not a continuous recording of temperature and salinity against depth, as an atmospheric sounding is of temperature and relative humidity against height. In an atmospheric sounding, this continuous record permits the determination of an inversion readily. At an oceanographic station, however, although a continuous trace of temperature against depth may be obtained through the use of the bathythermograph, the salinities are obtained from samples taken at discrete intervals by Nansen bottles or by the sea-sampler. If an inversion were present at the station, the chances of its showing up on the observation would be dependent on: (1) the magnitude of the vertical interval between samples; (2) the strength of the inversion; (3) the thickness of the inversion; and (4) the gradient of σ_t with depth both above and below the inversion.

Large intervals between samples, a rapid increase of σ_t with depth above or below the inversion, and a weak or shallow inversion would be factors precluding evidence of the inversion from showing up at the station.

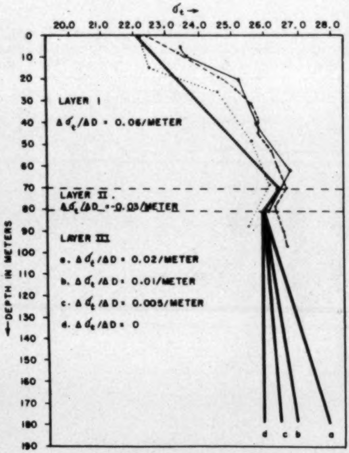

Fig. 2--Model station (see Table 1)
.... Station 3121, *Atlantis* Cruise 80, 1938
.-----. Station 20803, *Bigelow*, 1930
——— Average of the six stations showing inversions (no. 10, 11, 12, 17, 18, 19), *Albatross III*, 1948

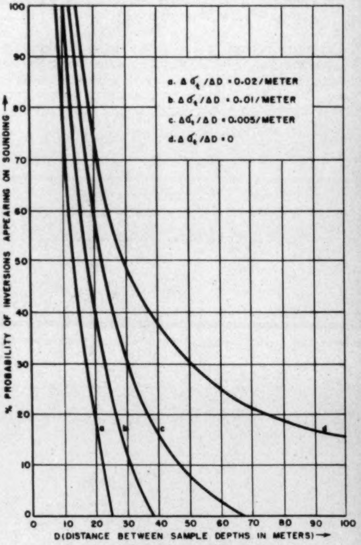

Fig. 3--Probabilities of the inversion's appearing at a station

For the model shown in Figure 2, chosen as representative of conditions in the area, the probabilities of the inversion's appearing at a station are shown in Figure 3. It is evident that the probabilities drop off rapidly with increasing intervals between samples. Since the average interval between samples for all stations in the area was approximately 50 m, it can be expected that fewer than 30 pct of the stations would show the inversions, even if they were present all the time, and even if all the stations reached to below the inversion level. Inasmuch as these last two conditions do not hold, it is not surprising that fewer than 17 pct of the stations in the area indicate the inversions.

Table 1--Data on inversions

Depth	Albatross III								
	Station 10, August 4, 1948 40° 08.4′ N, 70° 22.3′ W			Station 11, August 4, 1948 40° 04.4′ N, 70° 20.2′ W			Station 12, August 4, 1948 40° 00.0′ N, 70° 18.0′ W		
	Temperature	Salinity	σ_t	Temperature	Salinity	σ_t	Temperature	Salinity	σ_t
ft	°F	0/00		°F	0/00		°F	0/00	
Surface	68.0	....	....	68.5	....	....	71.5	....	....
23	64.0	34.07	24.68	70.0	32.92	22.87	71.8	32.86	22.56
66	53.0	33.06	25.61	69.5	35.41	25.40	68.0	35.07	25.28
82	45.8	33.08	25.85	65.0	35.18	25.40	63.2	34.80	25.41
104	44.9	33.24	26.04	60.0	35.03	26.28	60.5	35.19	26.00
127	46.0	33.44	26.10	59.0	35.14	26.15	60.0	35.57	26.15
161	47.0	33.55	26.10	57.5	34.42	25.71	61.0	....	....
185	48.5	34.32	26.55	57.5	35.34	26.41	60.8	35.12	25.99
205	50.7	34.44	26.45	58.5	35.39	26.43	56.0	35.17	26.50
235	52.0	34.82	26.62	57.8	35.68	26.70	56.5	35.55	26.71
264	54.0	34.78	26.41	57.0	35.19	26.46	56.5	35.11	26.46
299	53.0	....	....	55.8	35.46	26.78	55.5	35.46	26.78
316	52.0	....	....	55.0	35.45	26.82	55.0	35.37	26.75

Depth	Albatross III								
	Station 17, August 6, 1948 40° 02.0′ N, 69° 36.2′ W			Station 18, August 6, 1948 39° 58.9′ N, 69° 35.2′ W			Station 19, August 6, 1948 39° 55.8′ N, 69° 34.5′ W		
	Temperature	Salinity	σ_t	Temperature	Salinity	σ_t	Temperature	Salinity	σ_t
ft	°F	0/00		°F	0/00		°F	0/00	
Surface	69.6	....	....	74.8	....	....	77.2	....	....
23	71.3	34.79	24.13	74.9	33.97	22.93	77.5	34.85	23.17
66	70.9	35.59	24.79	71.6	35.01	24.24	77.4	34.85	23.18
82	68.9	35.30	24.88	65.8	35.11	25.18	72.6	34.99	24.07
104	64.7	35.39	25.54	65.0	34.88	25.12	61.1	34.60	25.42
127	63.9	35.44	25.69	61.3	34.85	25.59	56.5	....	....
161	61.9	34.88	25.53	59.7	34.78	25.74	54.2	34.90	26.47
185	62.1	35.38	25.88	58.0	35.22	26.28	55.7	35.17	26.51
205	58.3	35.20	26.23	57.7	35.22	26.32	55.6	35.19	26.54
235	58.4	35.71	26.61	56.9	35.66	26.75	55.6	35.49	26.77
264	59.1	35.49	26.36	57.8	35.39	26.43	56.7	35.56	26.69
299	55.9	....	....	56.3	....	....	57.2	....	....
316	54.4	....	....	56.0	35.59	26.80	57.0	35.73	26.79

Atlantis Cruise 80, Station 3121 August 24, 1938, 21h 17m Z 40° 07′ N, 71° 19′ W	
Depth	σ_t
m	
Surface	22.28
15	22.58
24	24.46
48	25.94
68	26.29
87	25.64
...	....

Bigelow Station 20803 June 25, 1930 40° 22′ N, 70° 35′ W			
Depth	Temperature	Salinity	σ_t
m	°C	0/00	
Surface	18.3	32.94	23.64
5	18.4	32.86	23.55
10	18.1	32.92	23.68
20	10.7	32.90	25.21
40	6.8	33.10	25.97
60	6.5	34.04	26.76
80	8.0	33.64	26.23

Stability of the inversion layer--The possibility exists that the inversion might be capable of self-maintenance because of viscous forces. This was investigated through the use of Rayleigh's stability criteria [BRUNT, 1950]. Rayleigh has shown that, because of the viscous forces present, a layer in which density increases with height can still be stable, provided that

$$(\rho_1 - \rho_0)/\bar{\rho} < 27\pi^4 \kappa \nu /(4gh^3) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where ρ_1 = density at top of layer

ρ_0 = density at base of layer

$\bar{\rho}$ = mean density of layer

g = force of gravity

h = thickness of layer

κ = coefficient of thermometric conductivity

ν = kinematic coefficient of viscosity

However, for the inversion layer (Fig. 2), $(\rho_1 - \rho_0)/\bar{\rho}$ is 10^{10} times too large for the layer to be stable, if the molecular coefficients for κ and ν are used. Even if the eddy coefficients are used instead, as suggested by BAUM [1951] and NEUMANN [1948], $(\rho_1 - \rho_0)/\bar{\rho}$ is still 50 times too large for the layer to be stable. The inversions cannot be said, therefore, to be in any way stable, even taking into account internal viscous forces. Some creative force must be acting in order to maintain the density inversion in the face of the dissipative forces tending to break it down.

Determination of subsurface current velocities--South of Nantucket Island, the parallel of 40°N is the approximate separation line between the westward-flowing Gulf of Maine waters on the continental shelf, and the eastward-flowing slope waters [BIGELOW, 1927]. From the surface to a depth of approximately 40 m, there is little difference between the densities of the two water masses; below 40 m, according to unpublished Woods Hole data, the increase of density with depth is much greater in the slope waters than in the Gulf of Maine waters on the shelf. At the level of the inversions, the slope waters are considerably denser than the shelf waters. The effect of the tidal currents on the discontinuity surface between these two water masses was investigated. In order to determine this effect at different levels, it is necessary to compute the current velocities at the various levels desired, as actual subsurface current measurements are not available.

At any time and level, the total current D can be represented as the sum of two components, a constant current C, which is a function of depth but not of time, and consequently does not undergo accelerations, and a tidal component V, which is a function of both time and depth. At the surface of the water

$$D_h = C_h + V_h \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where the subscript h represents the surface conditions. Using the measured currents at Nantucket Lightship (Fig. 4) as representative of the area, values of C_h and V_h can be chosen such that their sum, D_h, agrees closely to the actual measured currents. The Ekman spiral equation, based on the assumption of no acceleration in the surface current, can then be used to determine the component C of the subsurface current caused by the constant surface current C_h.

However, the acceleration terms in V_h are of the same order of magnitude as the Coriolis force term, and cannot be neglected in computing the subsurface currents. An equation was derived which took into account the acceleration terms, and from which the tidal components of the subsurface currents were computed. Let

$$V_h = A_h e^{i\omega t} + B_h e^{-i\omega t}$$

where A_h and B_h are constants known from surface current measurements

$V = A_z e^{i\omega t} + B_z e^{-i\omega t}$ = subsurface tidal component

$Le^{i\omega t} + Me^{-i\omega t}$ = tidal forces affecting both V_h and V

n = kinematic coefficient of eddy viscosity

f = coriolis parameter

Figure 4 is a comparison between the actual currents and the currents computed from the equation

$$D_h = C_h + V_h = C_h + A_h e^{i\omega t} + B_h e^{-i\omega t}$$

where the real axis is taken in the direction of the actual current at time LZ - 3 (three hours before lunar transit), C_h = 3 cm/sec, A_h = 6 cm/sec, B_h = 37.1 cm/sec, and $\omega = 2\pi/12.42\ \text{hr}^{-1} = 1.4056 \times 10^{-4}\ \text{sec}^{-1}$. The computed currents closely approximate the actual currents.

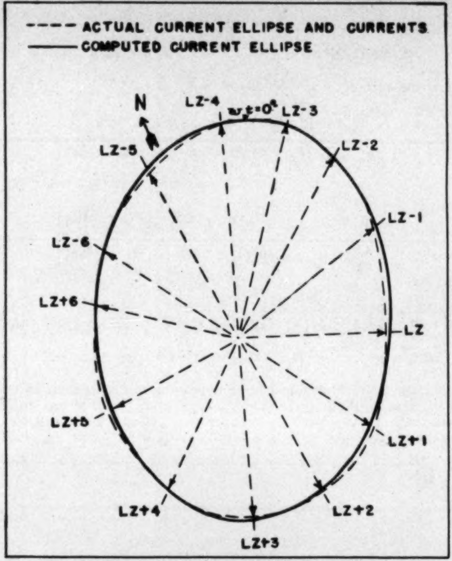

Fig. 4--Comparison of computed and actual current ellipse from Nantucket Lightship data

The assumptions are made that (1) V_h is not a function of z, $(dV_h/dz = d^2 V_h/dz^2 = 0)$, and (2) $dV/dx = dV/dy = 0$. The boundary conditions (BC) used are (1) $V = 0$, $A = 0$, $B = 0$ at $z = 0$, at the bottom of the ocean; and (2) $V = V_h$, $A = A_h$ and $B = B_h$ at $z = h$.

From the equations of motion

$$\partial V/\partial t = -fiV + Le^{i\omega t} + Me^{-i\omega t} + n\,\partial^2 V/\partial z^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$\therefore\ i\omega(Ae^{i\omega t} - Be^{-i\omega t}) = -fi(Ae^{i\omega t} + Be^{-i\omega t}) + Le^{i\omega t} + Me^{-i\omega t} + n(A''e^{i\omega t} + B''e^{-i\omega t}) \ldots (4)$$

$$\therefore\ nA'' = i(f+\omega)A - L \qquad nB'' = i(f-\omega)B - M \quad \ldots\ldots\ldots\ldots (5)$$

$$\left.\begin{aligned} \therefore\ A &= L/i(f+\omega) + \alpha_1 e^{-z[i(f+\omega)/n]^{1/2}} + \alpha_2 e^{z[i(f+\omega)/n]^{1/2}} \\ B &= M/i(f-\omega) + \beta_1 e^{-z[i(f-\omega)/n]^{1/2}} + \beta_2 e^{z[i(f-\omega)/n]^{1/2}} \end{aligned}\right\} \ldots\ldots\ldots (6)$$

where α_1, α_2, β_1, and β_2 are constants of integration.

Letting $i(f+\omega)/n = R^2$ and $i(f-\omega)/n = S^2$

$$A = L/R^2 n + \alpha_1 e^{-Rz} + \alpha_2 e^{Rz} \qquad B = M/S^2 n + \beta_1 e^{-Sz} + \beta_2 e^{Sz} \quad \ldots\ldots (7)$$

From BC (1), that at $z = 0$, $V = 0 = A = B$

$$0 = L/R^2 n + \alpha_1 + \alpha_2 \qquad 0 = M/S^2 n + \beta_1 + \beta_2 \quad \ldots\ldots\ldots\ldots (8)$$

Therefore

$$\alpha_1 = -(L/R^2n + \alpha_2) \qquad \beta_1 = -(M/S^2n + \beta_2) \tag{9}$$

From BC (2), that at the surface, $z = h$, $V = V_h$, $A = A_h$, $B = B_h$

$$\left.\begin{aligned} A_h &= L/R^2n + \alpha_2 e^{Rh} - [\alpha_2 + L/R^2n]\, e^{-Rh} \\ B_h &= M/S^2n + \beta_2 e^{Sh} - [\beta_2 + M/S^2n]\, e^{-Sh} \end{aligned}\right\} \tag{10}$$

Therefore

$$\left.\begin{aligned} \alpha_2 &= [A_h - L/R^2n\,(1 - e^{-Rh})]/(e^{Rh} - e^{-Rh}) \\ \beta_2 &= [B_h - M/S^2n\,(1 - e^{-Sh})]/(e^{Sh} - e^{-Sh}) \end{aligned}\right\} \tag{11}$$

Therefore

$$\begin{aligned} V = {} & \left\{L/R^2n\,(1 - e^{Rz}) - [A_h - (L/R^2n)\,(1 - e^{Rh})] \sinh Rz/\sinh Rh\right\} e^{i\omega t} \\ & + \left\{M/S^2n\,(1 - e^{Sz}) - [B_h - (M/S^2n)\,(1 - e^{Sh})] \sinh Sz/\sinh Sh\right\} e^{-i\omega t} \end{aligned} \tag{12}$$

Physically speaking, L and M are quantities appearing in the tidal potential, and they in turn determine A_h and B_h, that is, the surface current. Actually, L and M are impossible to ascertain for a partly bounded body of water such as the area in question. They must be expressed in terms of the observable quantities A_h and B_h (the surface current). If $Le^{i\omega t} + Me^{-i\omega t}$ represent the forces causing the tidal currents, then they must satisfy the equations of motion for the surface tidal current. Therefore

$$\partial V_h/\partial t = -fiV_h + Le^{i\omega t} + Me^{-i\omega t} \tag{13}$$

Therefore

$$L = i\,(f + \omega)\, A_h \qquad M = i\,(f - \omega)\, B_h \tag{14}$$

Substituting these values in (12), we get

$$V = A_h\,[1 + \sinh R(z - h)/\sinh Rh]\, e^{i\omega t} + B_h\,[1 + \sinh S\,(z - h)/\sinh Sh]\, e^{-i\omega t} \tag{15}$$

The complete solution for (15) with the real and imaginary components separated is

$$\begin{aligned} V = {} & A_h \left\{\cos\omega t - [(\cos\omega t)\,(J_1K_1 + J_2K_2) - (\sin\omega t)\,(J_1K_2 - J_2K_1)]/(K_1^2 + K_2^2)\right\} \\ & + B_h \left\{\cos\omega t - [(\cos\omega t)\,(J_3K_3 + J_4K_4) - (\sin\omega t)\,(J_3K_4 - J_4K_3)]/(K_3^2 + K_4^2)\right\} \\ & + iA_h \left\{\sin\omega t - [(\sin\omega t)\,(J_1K_1 + J_2K_2) + (\cos\omega t)\,(J_1K_2 - J_2K_1)]/(K_1^2 + K_2^2)\right\} \\ & - iB_h \left\{\sin\omega t - [(\sin\omega t)\,(J_3K_3 + J_4K_4) + (\cos\omega t)\,(J_3K_4 - J_4K_3)]/(K_3^2 + K_4^2)\right\} \end{aligned} \tag{16}$$

where

$$J_1 = \sin[(f + \omega/2n)^{1/2}\,(h - z)] \cosh[(f + \omega/2n)^{1/2}\,(h - z)]$$

$$J_2 = \cos[(f + \omega/2n)^{1/2}\,(h - z)] \sinh[(f + \omega/2n)^{1/2}\,(h - z)]$$

$$J_3 = \sin[(\omega - f/2n)^{1/2}\,(h - z)] \cosh[(\omega - f/2n)^{1/2}\,(h - z)]$$

$$J_4 = \cos[(\omega - f/2n)^{1/2}\,(h - z)] \sinh[(\omega - f/2n)^{1/2}\,(h - z)]$$

$$K_1 = \sin[(f + \omega/2n)^{1/2}\,h] \cosh[(f + \omega/2n)^{1/2}\,h]$$

$$K_2 = \cos[(f + \omega/2n)^{1/2}\,h] \sinh[(f + \omega/2n)^{1/2}\,h]$$

$$K_3 = \sin\left[(\omega - f/2n)^{1/2}\, h\right] \cosh\left[(\omega - f/2n)^{1/2}\, h\right]$$

$$K_4 = \cos\left[(\omega - f/2n)^{1/2}\, h\right] \sinh\left[(\omega - f/2n)^{1/2}\, h\right]$$

In (15), A_h and B_h are assumed to be real. Although this satisfies the data in this particular case, the solution is less general than when they are both assumed to be complex. If the real parts of both constants are denoted by the superscript R, and the imaginary parts by the superscript I, then

$$V_h = (A_h^R + B_h^R)\cos\omega t - (A_h^I - B_h^I)\sin\omega t + i\left[(A_h^R - B_h^R)\sin\omega t + (A_h^I + B_h^I)\cos\omega t\right] \ldots (17)$$

In this case, any phase difference may exist between the velocity components parallel to the real and imaginary axes. If the imaginary parts of A_h and B_h are 0, this simplifies to the form previously shown. The solution for V, when V_h is in the form in (17), is

$$\begin{aligned}
V = {} & A_h^R\left\{\cos\omega t - \left[(\cos\omega t)(J_1K_1 + J_2K_2) - (\sin\omega t)(J_1K_2 - J_2K_1)\right]/(K_1^2 + K_2^2)\right\} \\
& + B_h^R\left\{\cos\omega t - \left[(\cos\omega t)(J_3K_3 + J_4K_4) - (\sin\omega t)(J_3K_4 - J_4K_3)\right]/(K_3^2 + K_4^2)\right\} \\
& - A_h^I\left\{\sin\omega t - \left[(\sin\omega t)(J_1K_1 + J_2K_2) + (\cos\omega t)(J_1K_2 - J_2K_1)\right]/(K_1^2 + K_2^2)\right\} \\
& + B_h^I\left\{\sin\omega t - \left[(\sin\omega t)(J_3K_3 + J_4K_4) + (\cos\omega t)(J_3K_4 - J_4K_3)\right]/(K_3^2 + K_4^2)\right\} \\
& - i\Big(A_h^R\left\{\sin\omega t - \left[(\sin\omega t)(J_1K_1 + J_2K_2) + (\cos\omega t)(J_1K_2 - J_2K_1)\right]/(K_1^2 + K_2^2)\right\} \\
& - B_h^R\left\{\sin\omega t - \left[(\sin\omega t)(J_3K_3 + J_4K_4) + (\cos\omega t)(J_3K_4 - J_4K_3)\right]/(K_3^2 + K_4^2)\right\} \\
& + A_h^I\left\{\cos\omega t - \left[(\cos\omega t)(J_1K_1 + J_2K_2) - (\sin\omega t)(J_1K_2 - J_2K_1)\right]/(K_1^2 + K_2^2)\right\} \\
& + B_h^I\left\{\cos\omega t - \left[(\cos\omega t)(J_3K_3 + J_4K_4) - (\sin\omega t)(J_3K_4 - J_4K_3)\right]/(K_3^2 + K_4^2)\right\}\Big) \ldots\ldots (18)
\end{aligned}$$

where the J's and the K's have the same value as in (16).

At 40° N, $f = 0.9375 \times 10^{-4}\ \text{sec}^{-1}$. The value of the kinematic coefficient of eddy viscosity, n, is assumed to be 300 gm/cm sec, a value which agrees with those found by FJELDSTAD [1936]. In this area, the depth of the water h is approximately 100 m. For this value of h, e^{Rh} is 3.678×10^5 times as large as e^{-Rh}, and e^{Sh} is 2.66×10^2 times as large as e^{-Sh}. Consequently, e^{-Rh} and e^{-Sh} can be disregarded in relation to e^{Rh} and e^{Sh}, respectively, without introducing any appreciable error. By means of this simplification, (15) becomes

$$V = A_h e^{i\omega t}(1 - e^{-Rz}) + B_h e^{-i\omega t}(1 - e^{-Sz}) \ldots\ldots\ldots\ldots\ldots\ldots (19)$$

Using (19), the tidal currents at different times and levels were computed. By adding to these the component C contributed at each level by the constant current C_h, and determined by the Ekman spiral equation, the total current D for each level and time was obtained.

The current spirals traced out by the ends of the velocity vectors are shown in Figure 5, as are the semi-diurnal tidal current ellipses for each level. From this figure, several facts can be ascertained. The greatest current velocities are found at or just above the 40-m level. It is evident that in the friction layer the major axes of the current ellipses are oriented approximately north-south. At higher levels, the axes rotate in a clockwise direction, so that above the friction layer they are almost northeast-southwest. This agrees with the findings of FJELDSTAD [1936] and others.

It is also evident that the trajectories of particles in the upper levels cover a much wider area than those of particles in the lower levels. This would indicate extensive overrunning of the lower layers by the upper layers every tidal cycle. This overrunning imposed on a discontinuity surface such as is known to exist between the two water masses in this region could well be the cause of the inversions found here. For this reason, trajectories of particles at different levels were graphed (Fig. 6). To determine the onshore effect of the different trajectories, the hour when the surface current was parallel to the shore, moving to the west (at the 270° position) was taken as a starting point. Table 2 shows the net onshore movement of the waters at different levels at the end of six hours, and the maximum onshore displacement for each level during the entire tidal period.

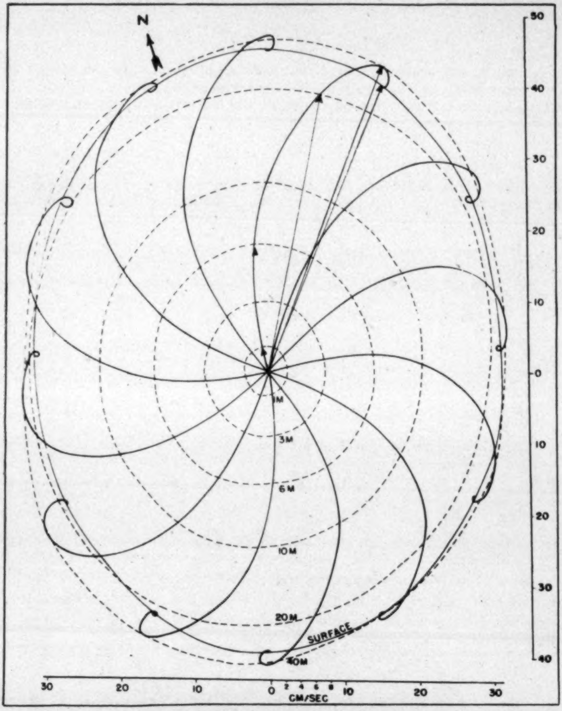

Fig. 5--Computed tidal currents and ellipses

Table 2--Onshore displacement of water

Level (above bottom)	Displacement	
	After six hours	Maximum
m	m	m
Surface	6775	6777
80	6845	6860
60	6988	7005
40	6975	7001
20	5657	5668
10	3424	3511
6	2168	2265
3	1122	1199
1	397	431

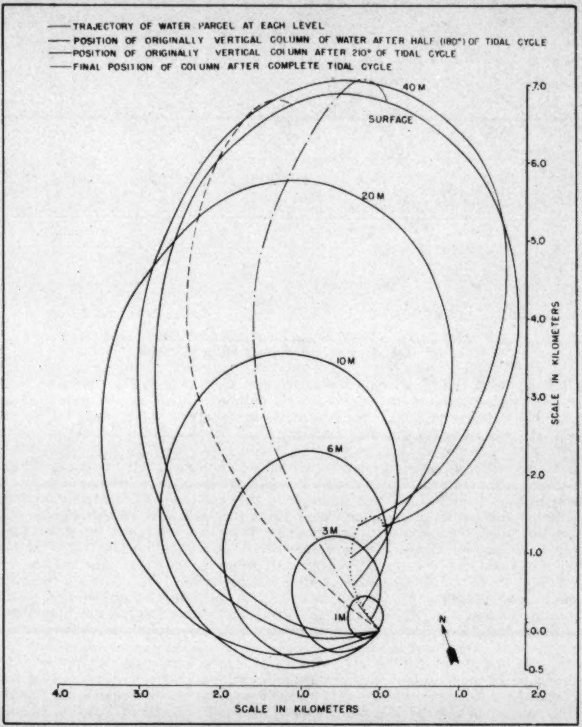

Fig. 6--Trajectories of particles at different levels

Effect of tidal currents on discontinuity surface--A column of water which was originally vertical at the beginning of this onshore movement would be displaced varying amounts at different levels, and would no longer be vertical. Figure 7a presents the successive positions assumed by such an originally vertical column. The time between each position is that required by the surface current to turn through a 30° arc of the tidal cycle, or one hour two minutes. At first, when the surface current is moving parallel to the shore, the waters in the lower levels are moving slightly further offshore. The waters near the top start moving onshore first. The greatest onshore movement is effected by the waters between 40 m and 60 m above the bottom. At the turn of the tide, the upper level waters recede first, followed more slowly by the waters in the middle and lower levels. Eventually the waters return to the position indicated at the end of the tidal cycle in Figure 6. This is the position the waters would have assumed had there been no tidal currents at all, but only the constant surface current of three cm/sec flowing during the entire period in the direction indicated.

However, it cannot be said that the frontal discontinuity between the two water masses is vertical, or nearly so. An estimate of the maximum slope it might have can be made from the temperature and salinity distributions, which differentiate the two water masses clearly [SPILHAUS,

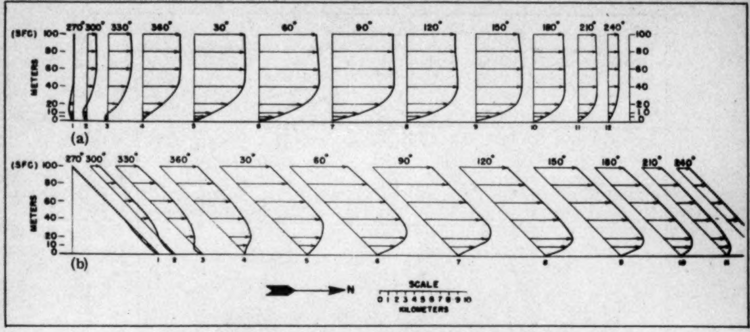

Fig. 7--Onshore displacement of a column of water (a) originally vertical; (b) with an original slope of 1:100

EHRLICH, and MILLER, 1950]. From a depth of 50 ft to a depth of 200 ft, Station 16 is definitely in the shelf water, and Station 17, 3 1/8 mi south, is definitely in the slope water. The maximum slope which a discontinuity could have between these two levels is 1/110. This can be said to be the maximum slope possible for this discontinuity.

Figure 7b indicates the effect of the tidal currents on a discontinuity having a slope of 1/100, neglecting mixing. The waters at the different levels move onshore in the same manner as previously described for a vertical column. Whereas in the case of the vertical column, the top of the inversion was at about 50 m above the bottom, in this case it is at a height of approximately 30 m. Above this level, the discontinuity maintains a slope in the same direction but not to the same degree as the original slope. As the waters recede during the second half of the tidal period, the top of the inversion is successively lowered until it disappears against the bottom. The inversion level of 30 m above the bottom indicated above corresponds closely with the conditions actually found. If the original slope had been 1/400, an inversion would still have been produced, but the top would have been at a height of only eight meters above the bottom, and probably could not have been measured.

It can be said, therefore, that the effect of the tidal currents on a frontal discontinuity in this region is to induce extensive overrunning, causing an inversion to be produced during each tidal period, and that the greater the original slope of the discontinuity, the lower is the top of the inversion. The inversions as originally found were at approximately 30 m above the bottom, indicating a slope of 1/100, close to the maximum possible slope as calculated from the soundings.

Comparison with cases of instability in other parts of the Atlantic Ocean--Instability has been reported in other regions of the Atlantic Ocean. SCHUBERT [1935], in comparing the results of the 1925-1927 Meteor findings with previous surveys, listed many stations showing instability either in the upper 100 m, or near the bottom in isolated deeps. There are, however, certain dissimilarities between these cases and those off Nantucket.

There are numerous examples of very weak instability in the bottom layers in isolated deeps, such as the Angola Deep and the Philippine Deep. The absolute magnitude of the negative value of $10^8 E$, however, was greater than unity in only one case, and in that case Schubert indicates that the computed value (-8) was caused by an error in salinity. All values of instability in the bottom layers are within the limits of observational error, and no evidence of either great stability or great instability is found. The condition in these deeps is most probably simply one of neutral stability in the bottom layer. Heat flux may be coming from the Earth, as has sometimes been postulated to explain the instability, but the magnitudes of the instabilities are so small as to lead to the assumption that they are really due to observational error, and that the heat flux is so small that convection has sufficient time to cause the entire lower layers to become and remain neutrally or indifferently stable.

In the top 100 m, however, there are numerous examples of instability whose magnitudes are too large to be explained by observational error. Here, instability at lower depths (50 to 75 m, and 75 to 100 m) is almost invariably associated with unstable conditions above, all the way up to the surface. The data indicate that the instability is greatest and is most frequent in the top 25 m (43 pct of the soundings), and extends a variable distance downwards, in five per cent of the soundings reaching as far as the 100-m depth. This differs from the Nantucket situation, in which the instability at 70 to 80 m underlies stable layers above.

No correlation between the occurrence of instability and the time of day was found. However, there is some evidence presented by Schubert to indicate that the frequency of instability in the top 100 m is dependent on the season. Two east-west sections taken in winter presented many soundings with instability in the upper layers. A third cross-section, lying between the two, and taken in summer, had many fewer stations showing instability, the instability was weaker, and did not extend down as far as in the case of the soundings taken in winter.

SCHUBERT [1944] includes Meteor data from 1938. A study of these data reveals one interesting case in which there is a definite correlation between instability in the 60 to 70 m layer and the tidal period. This is at Meteor Station 385. Since the Nantucket instability cases were also correlated with the tidal period, the data at this station were investigated in some detail for comparison.

At Station 385 (16° 48.3′ N, 46° 17.1′ W), 60 consecutive hourly samplings were made February 12-14, 1938. An average of all the observations shows an unstable surface layer (σ_t = 24.80 at the surface, and 24.73 at five meters). Below this surface layer, there is an almost homogeneous (with respect to density) layer down to 60 m (σ_t = 24.77). From here down, there is a rapid increase of σ_t with depth, σ_t averaging 25.57 at 100 m. During this 60-hr period, the layers between 50 and 90 m show an increase of σ_t with depth: 50-60 m, 11 times; 60-70 m, 7 times; 70-80 m, 7 times; and 80-90 m, 0 time. There was a strong correlation between the time of appearance of the instability and the tidal period. The reason for this correlation is readily seen, however, when the depth of the base of the almost homogeneous upper layer is plotted against time, and the unstable layers indicated on the graph (Fig. 8). It is evident that there are internal waves with a tidal period on the boundary between the upper homogeneous layer and the lower, strongly stable layer. The cases of instability are all found in the upper homogeneous water. When the boundary between the two layers sinks in the trough of the wave, this upper water mass extends to greater depths, and weak instability becomes possible down to depths of 80 m. When the boundary rises, at the crest of the wave, the homogeneous waters, and consequently the cases of instability, are confined to higher levels, usually above the 50 or 60 m depth line. The correlation of instability at 50 to 80 m with the tidal period, therefore, is due to the alternate raising and lowering of the boundary between the two water masses by the internal tidal waves, and the tidal oscillation is associated with the time of the instabilities at particular depths, but not with the cause. This is markedly different from the condition off Nantucket, where the unstable layer has stable layers both above and below it, and where the horizontal tidal currents are the actual cause of the instability.

The Nantucket cases differ from those cases of instability reported to date in other parts of the Atlantic. This is not to say that conditions in this vicinity are unique, and not found elsewhere. On the contrary, the results of this investigation indicate the possibility of similar occurrences in other areas on the borders of dissimilar water masses, as for instance, along the Cold Wall at the edge of the Gulf Stream, as well as in other similar areas.

Conclusions--The subsurface inversions south of Nantucket Island are found in conjunction with the discontinuity surface between the lighter, cooler, less saline shelf waters from the Gulf of Maine, and the denser, warmer, but more saline slope waters. They are apparently produced by the effect of the tidal currents on this discontinuity surface. They differ in the manner in which they are caused from the cases of instability reported by Schubert and others in other parts of the Atlantic.

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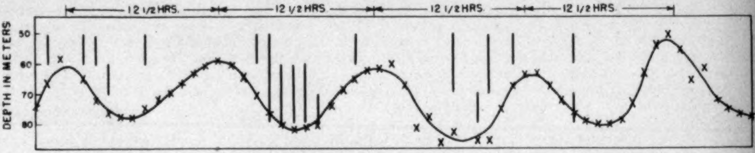

a. DEPTH OF DISCONTINUITY BETWEEN UPPER, ALMOST NEUTRALLY STABLE LAYER, AND LOWER STABLE LAYER. VERTICAL LINES INDICATE LAYERS THROUGH WHICH σ_1 INCREASES WITH DEPTH.

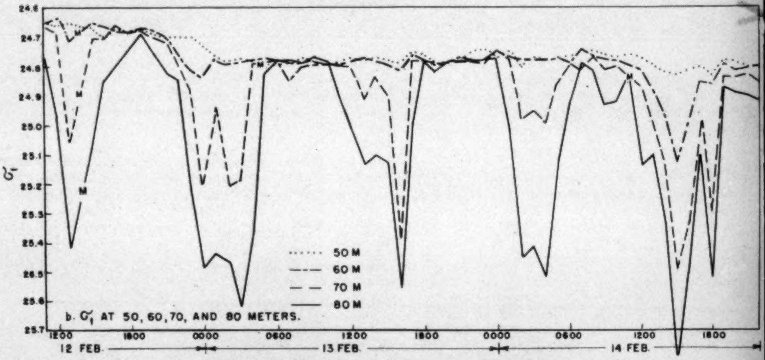

Fig. 8--Density changes with time at Meteor Station 385
(16° 48.3′ N, 46° 17.1′ W, February 12-14, 1938)

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NOTE ON A PREDICTION EQUATION FOR THE SURFACE LAYER OF A TWO-LAYER OCEAN

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(A. and M. College of Texas, Department of Oceanography, Contribution No. 33)

Abstract--Time changes in the thickness of a thin surface layer of a two-layer ocean are proportional to the curl of the wind stress if accelerations are sufficiently small.

Introduction--SVERDRUP [1942, p. 500], in speaking of the transport of water by the wind stress, says "... wind systems must, in certain regions, lead to an accumulation of light surface waters and, in other regions, to a rise of denser water from subsurface depths." We have exploited this idea in finding the response to be expected of a two-layer ocean to wind stresses which persist. It is well known that the wind stress causes a transport which is proportional to the square of the wind speed and directed to the right of the wind vector. It can be seen that if we have a region of weak winds to the right of a region of strong winds, as for example in Figure 1, there will be a tendency for water to accumulate between these regions.

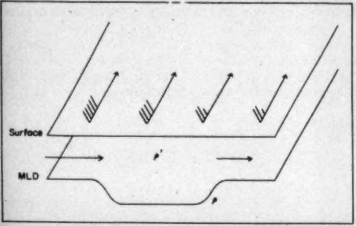

Fig. 1--The surface layer with density ρ' is transported to the right of the winds; the strong winds transport more water into the region in the center of the drawing than is transported out by the weak winds; the resulting accumulation of water pushes the deep water of density ρ away from the center of the drawing

In a two-layer ocean under certain conditions the accumulation leads to a change in the thickness of the surface layer which is shown to follow

$$\partial H/\partial t = (1/\rho' f)\,(\partial \tau_y/\partial x - \partial \tau_x/\partial y)$$

in which

H = thickness of a thin homogeneous top layer of a two-layer ocean
f = coriolis force
τ = wind stress
ρ' = density of surface fluid

Equations of motion--The equations of motion for the homogeneous upper layer with density ρ' can be written

$$Du/dt = -(1/\rho')(\partial p/\partial x) + fv - (1/\rho')(\partial \tau_{xz}/\partial z) \quad \text{.............} (1)$$

$$Dv/dt = -(1/\rho')(\partial p/\partial y) - fu - (1/\rho')(\partial \tau_{yz}/\partial z) \quad \text{.............} (2)$$

where τ_{xz} and τ_{yz} are the stresses in the water.

We concern ourselves with the portion of the pressure and wind field that persists. We assume that the currents, set up by these pressures and the winds, change with time in such a way that we can say in (1) and (2)

$$|Du/dt| << |fv| \qquad |Dv/dt| << |fu|$$

These assumptions are discussed in the appendix.

Then (1) and (2) become

$$fv = (1/\rho')\,(\partial p/\partial x) + (1/\rho')\,(\partial \tau_{xz}/\partial z) \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$fu = (1/\rho')\,(\partial p/\partial y) - (1/\rho')\,(\partial \tau_{yz}/\partial z) \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

We assume that all currents are insignificant near and below the interface. These small currents result in negligible values of the stresses near the interface. (We cannot say the currents are zero near the interface because the water moves to bring about adjustments in the interface, following (3), but we assume these motions near the interface are primarily vertical in the upper layer of water and the total horizontal transport in the lower layer is spread over a very deep layer and the resulting currents are extremely small.)

Continuity of mass--Though changes in the mean level of the ocean can possibly bring about quite large pressure gradients in the homogeneous water layer, the error introduced in the thickness of the upper layer by using the water surface as an origin rather than some fixed level line is small. Changes in the thickness of this layer are observed to be in the order of tens of feet, and water-level changes are observed to be in the order of feet, at least as measured on coasts. We can say from observation, therefore, that our model should have such small density differences that when water in the upper layer accumulates in an area it pushes the interface down and bottom water out of the way rather than raising the water surface by any significant amount.

The integral form of the continuity equation then becomes

$$\partial H/\partial t = (\partial/\partial x)\int_{-H}^{s} u\,dz + (\partial/\partial y)\int_{-H}^{s} v\,dz$$

We define T_x and T_y such that this can be written

$$\partial H/\partial t = -\,(\partial T_x/\partial x + \partial T_y/\partial y) \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Computation of the divergence of water transport--We wish to find suitable values of the divergence, $\partial T_x/\partial x + \partial T_y/\partial y$. We do this by eliminating the pressure from (3) and (4) and integrating the resulting equation in the vertical direction. To eliminate the pressure we differentiate (3) with respect to y and (4) with respect to x and we find

$$f\,(\partial v/\partial y) = (1/\rho')\,(\partial^2 p/\partial x\partial y) + (1/\rho')\,(\partial^2 \tau_{xz}/\partial z\partial y)$$

$$f\,(\partial y/\partial x) = -\,(1/\rho')\,(\partial^2 p/\partial x\partial y) - (1/\rho')\,(\partial^2 \tau_{yz}/\partial z\partial x)$$

We add these equations to get

$$f\,(\partial u/\partial x + \partial v/\partial y) = -\,(1/\rho')\,(\partial^2 \tau_{yz}/\partial z\partial x - \partial^2 \tau_{xz}/\partial z\partial y)$$

This equation is integrated from $z = -H$ to $z = s$ resulting in

$$f\int_{-H}^{s} (\partial u/\partial x + \partial v/\partial y)^{dz} = (1/\rho')\int_{-H}^{s} (\partial^2 \tau_{yz}/\partial x\partial z - \partial^2 \tau_{xz}/\partial y\partial z)\,dz$$

This can be rewritten, using Leibnitz rule for differentiating integrals

$$f(\partial/\partial x)\int_{-H}^{s} u\,dz + f(\partial/\partial y)\int_{-H}^{s} v\,dz + \overset{(2)}{fu_H\,(\partial H/\partial x)} + \overset{(3)}{fv_H\,(\partial H/\partial y)} - \overset{(4)}{fu_s\,(\partial s/\partial x)} - \overset{(5)}{fv_s\,(\partial s/\partial y)}$$

$$= -\,(1/\rho')\,(\partial\tau_{yz}/\partial x - \partial\tau_{xz}/\partial y)\Big|^{s} + \overset{(6)}{(1/\rho')\,(\partial\tau_{yz}/\partial x - \partial\tau_{xz}/\partial y)\Big|^{H}}$$

We now use some of our assumptions:

In the last equation, items (2) and (3) can be neglected because velocities are very small at the bottom of the surface layer and slopes due to large scale wind systems are small.

Items (4) and (5) can be neglected because the slope of the water surface is very small.

Item (6) can be neglected because velocities and stresses are very small at the bottom of the surface layer.

Using these facts and the definitions in (5), we are now left with the equation

$$f\,(\partial T_x/\partial x + \partial T_y/\partial y) = -(1/\rho')\,(\partial \tau_y/\partial x - \partial \tau_x/\partial y) \ldots\ldots\ldots\ldots (6)$$

We substitute this result in (5) and find

$$\partial H/\partial t = (1/\rho' f)\,(\partial \tau_y/\partial x - \partial \tau_x/\partial y) \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Thus we have derived the prediction equation mentioned in the introduction.

Acknowledgments--This paper is the result of the combination of two series of discussions, the first with R. O. Reid and Carter R. Sparger concerning water-level changes in response to wind stresses; and the second with Robert A. Gilcrest, Glenn H. Jung, and Dale F. Leipper concerning thermocline-depth changes. This work was supported by the Office of Naval Research on Contract N7onr-48703, NR 083-061.

APPENDIX

The assumption that the accelerations are small enough to allow the geostrophic approximation (or its equivalent) to be made is worthy of investigation.

One equation of motion can be written

$$DV_n/dt = -(1/c)\,(\partial p/\partial n) - fV_s$$

where V_n is the component normal to the original velocity vector x_o, y_o, t_o (that is any point chosen for the purpose of considering the equation above); and V_s is the component parallel to the original velocity vector. Our approximation used in obtaining (3) and (4) can be expressed

$$\left| DV_n/dt \right| << \left| fV_s \right|$$

If the flow is so extremely curved or is changing direction so fast that at the end of a day $V_n = V_s$ (when measured from the original direction) an extreme condition exists. If we can show that

$$\left| V_s/\text{day} \right| << \left| fV_s \right|$$

is true then our approximation is obviously true for the more usual cases where $V_n < V_s$. Now as is well known

$$f = 4\pi \sin\phi\, V_s/\text{day}$$

so that the problem expressed above becomes

$$\left| V_s/\text{day} \right| << \left| 4\pi \sin\phi\, V_s/\text{day} \right|$$

or is

$$1 << 12.5 \sin\phi$$

Thus, if we will say $1 << 6\ 1/4$, then for every latitude above 30° we can say that

$$\left| DV_n/dt \right| << \left| fV_s \right|$$

for all current systems in which V_n does not exceed a magnitude V_s during one day. $V_n = V_s$ after 24 hr is an extreme condition. In order for the condition $V_n = V_s$ to be true after one day for a current of three knots, a radius of curvature of less than 50 mi is required. The gyre of the eastern Gulf of Mexico noted on a cruise of the Alaska (Cruise 4-2A) in January, 1952, had a current of one knot and a radius of curvature of 60 mi.

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HYDRAULIC HEAD LOSS AT THE INTERFACE BETWEEN UNIFORM SANDS OF DIFFERENT SIZES

Frank N. Leatherwood and Dean F. Peterson, Jr.

Abstract--The hydraulic head loss for flow occurring at an interface between sands or gravels of different sizes was studied by experiment. Dimensional analysis was used in formulating the experiments and in analyzing the data which led to a simple relationship in which the hydraulic head loss at the interface is a function of the mean diameter of the smaller-sized sand or gravel, the Reynolds number for the flow through the smaller-sized gravel, and an empirical constant which appears to depend principally on the mean size and size distribution characteristics of the two sizes of sand or gravel. The experiments provided an opportunity to observe the action of sands or gravels used as filters and observations confirmed the opinion of Terzaghi and others that for uniform-sized sands the ratio of the mean diameter of the filtering sand to that of the sand to be filtered must not exceed approximately five in order that the smaller-sized material be excluded from the pores of the larger-sized material.

Introduction--Filters of sand or gravel are extensively used in many types of engineering works. While most frequently thought of in connection with the treatment of water or sewage, or in chemical engineering, they are of great importance in developing or assuring stability of Earth structures subjected to seepage forces, particularly Earth dams and wells. When used for wells they are usually called "envelopes."

The physical principle which makes filters possible is that, in a packing, the size of the pores is several times smaller than the size of the particles. Filters properly designed must allow the free passage of water but prevent the erosion of the soil or sand particles which are to be filtered. A desirable filter, therefore, is one in which the pores are so small that the filtered material will not enter them but large enough to allow the greatest freedom of percolation. The particles at the outflow face of the filter must be of sufficient mass that they are not eroded under the seepage forces. Often several layers of sand or gravel are required in order to achieve both filtration and stability. The desirable ratio of particle size between filter and filtered material has been investigated by BERTRAM [1939], U. S. WATERWAYS EXPERIMENT STATION [1941], U. S. BUREAU OF RECLAMATION [1947], and others.

Near the boundary or interface between two packings consisting of particles of different sizes the permeability of the filter packing is greatly decreased for a short distance as a result of the partial entry of the small-sized particles into the filter pores. The study herein reported was concerned with the piezometric head loss in this region.

Theoretical analysis--The flow of water through a filter is usually in the viscous range and is described by the law of Darcy

$$V = Ki$$

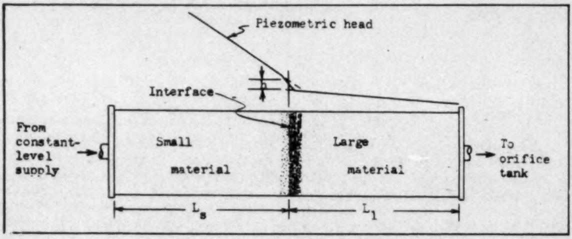


Fig. 1--Diagrammatic sketch of apparatus where V is the bulk velocity, K is the hydraulic conductivity, and i is the hydraulic gradient. For the purposes of this study, the head loss h assigned to the interface was considered to be an equivalent drop of head in the plane of the interface as shown by Figure 1. It was defined as the vertical distance between the intersection of the upstream and downstream piezometric surfaces with the interface plane. Considering the more important characteristics of the fluid, the packings, and the flow conditions; one may write the symbolic relationship

$$F_1\,(\rho,\ \mu, D_\ell, D_s,\ \sigma_\ell,\ \sigma_s,\ \alpha_\ell,\ \alpha_s, h, V_\ell, V_s) = 0 \quad \ldots\ldots\ldots\ldots (1)$$

where

ρ is the mass density
μ is the viscosity
D_ℓ, D_s are the mean diameters of the large- and small-sized particles
σ_ℓ, σ_s are the standard deviations of the large- and small-sized particles respectively
α_ℓ, α_s are the porosities of the packings of large- and small-sized particles respectively
V_ℓ, V_s are the upstream and downstream bulk velocities
F designates a functional relationship

If experiments are conducted at a standard value of porosity, α_ℓ and α_s may be eliminated; and further if they are conducted using packings in a tube of constant cross-section $V_\ell = V_s = V$. The remaining variables may be related in the expression

$$h/D_s = F_2\,(VD_s\,\rho/\mu, D_\ell/D_s,\ \sigma_\ell/D_s,\ \sigma_s/D_s) \quad \ldots\ldots\ldots\ldots (2)$$

Since the materials used in these experiments were of nearly uniform size, screened between two standard sieve sizes; the authors assumed that the variables σ_ℓ/D_ℓ and σ_s/D_s would not be important. Experiments indicated that the size of the large particles had little influence, however, and that h was influenced largely by the size of the small particles, Reynolds number $VD_s\,\rho/\mu$, and some combination of the uniformity parameters σ_ℓ/D_ℓ and σ_s/D_s.

Apparatus and materials--The permeameter in which the packings were placed was a six-inch diameter plastic tube 24 inches long to which wooden plates could be attached at the ends. The length of the tube was perforated for a number of piezometer taps which were connected to a manometer bank. Water from the city mains of Fort Collins was supplied from the 2000-gallon storage tank in which a constant level was maintained by an overflow pipe. The effluent water was discharged into a small tank equipped with orifices which were calibrated to determine the rate of flow. A photograph of the apparatus and a diagrammatic sketch are shown in Figure 2.

All of the sands and gravels were screened from gravel deposits of the Cache la Poudre River. The seven sizes used may be described in terms of Tyler sieve numbers as 40-60, 30-40, 20-30, 14-20, 10-14, 5-8, and 3-4 mesh respectively. The 10-14 and 14-20 samples were used as both fine and coarse material. In addition one specimen having graded particle size was used. Gradation curves were obtained for the various samples and are shown in Figure 3. The standard deviations of particle size were computed by the formulas

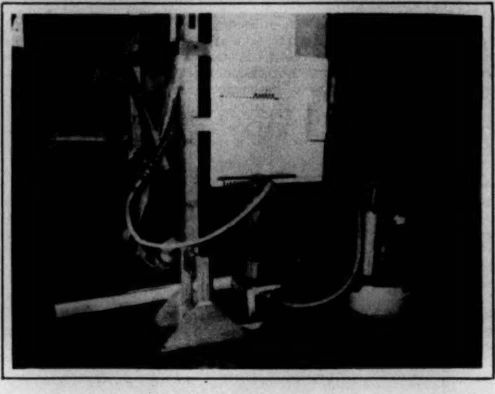
For 3-4 and 5-8 mesh: the standard deviation = Range of particle sizes/ $\sqrt{12}$

For other than 3-4 and 5-8 mesh: the standard deviation = $(D_{90} - D_{10})/2.6$

Various size combinations used were as follows

Coarse material		Fine material
(3-4)-mesh	with	(5-8)-, (10-14)-, (14-20)-mesh
(5-8)-mesh	with	(10-14)-, (14-20)-, (20-30)-, (30-40)-, (40-60)-mesh
(10-14)-mesh	with	(14-20)-, (20-30)-, (30-40)-, (40-60)-mesh, Graded
(14-20)-mesh	with	(20-30)-, (30-40)-, (40-60)-mesh

The packings were placed under water and the volume porosity was measured by the water displacement. Care was taken so that packings were uniformly placed and so that the interface plane was clearly defined and carefully located. The tests were conducted with the tube in a vertical position with the fine material on top. Before starting a test, water was allowed to flow slowly upward through the tube in order to remove any trapped air in the interstices. Flow was started at a slow rate and increased by increments to the capacity of the apparatus. A period of 30 minutes



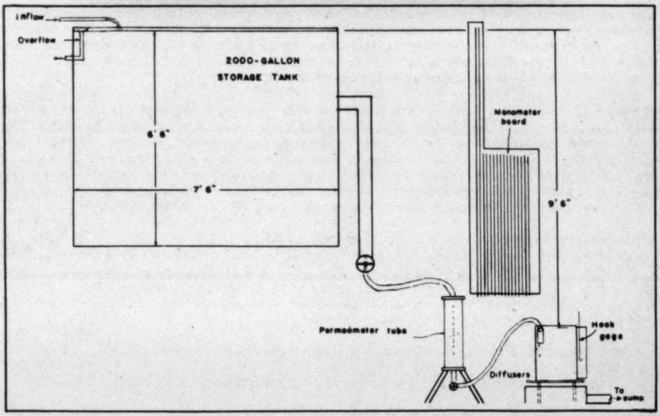

Inflow
Overflow
2000-GALLON
STORAGE TANK
6' 6"
7' 6"
Manometer board
9' 6"
Permeameter tube
Hook gage
Diffusers
To sump

Fig. 2--Photograph and diagram of apparatus

was allowed for each of the first two tests of each series in order for full stability to develop. For succeeding tests in any series the stabilizing period was reduced to 15 minutes. The piezometers were read, the upstream and downstream piezometric surfaces plotted, and h computed for each test.

Head loss at the interface--The data obtained are presented in Figure 4. Curves of h/D_s as a function of Reynolds number for various values of the product of the uniformity parameters for the two sands are shown on this figure. The results form a family of straight lines having a slope of unity when plotted logarithmically. The linear relationship of head loss and Reynolds number indicated that the flow remained in the viscous range for the various tests.

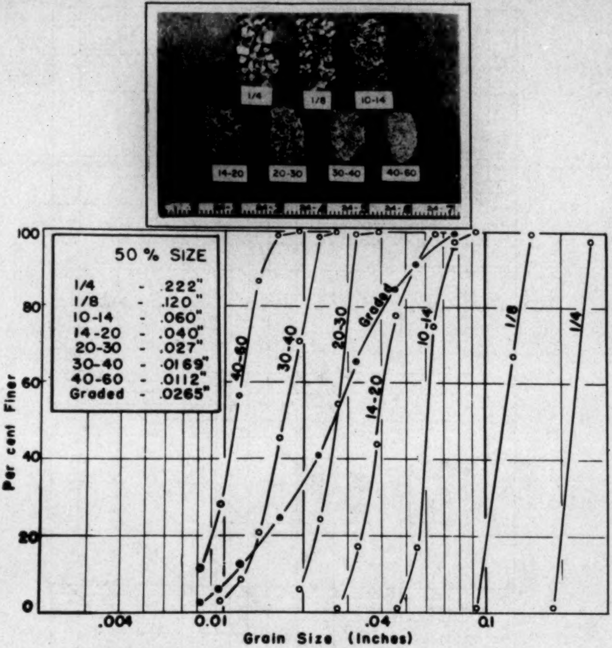


Fig. 3--Photograph of materials and grain-size distribution curves

The equation for head loss at the interface may be written in the form

$$h/D_s = C R_e \qquad (3)$$

where C is the value of h/D_s for a Reynolds number $R_e = 1$.

If values of C are plotted logarithmically as a function of $\sigma_s \; \sigma_\ell / D_s D_\ell$ (Fig. 5), the points plot approximately on a straight line. Using the method of least squares, the best fit through these points is given by

$$C = 1.02 \times 10^8 \left[(\sigma_s \; \sigma_\ell)/(D_s D_\ell)\right]^{4.6} \qquad (4)$$

Eq. (3) should be useful for predicting the piezometric head loss at the interface between uniform sands of different sizes. Reference to Figure 4 should assist the investigator in selecting a value of C to use in this equation. Of major importance is the gradation property of the sand, however, as is shown by (4). This equation was developed principally using sands having a narrow range of grain sizes. Only one material with a fairly wide range of grain sizes was tested, and although C for this test agreed very closely with that predicted by (4), this equation should nevertheless be regarded as restricted to packings in which the grain-size range is relatively narrow.

Stability in filtration--If the ratio of the large-particle diameter to the small-particle diameter was too great, the small particles moved through the pores of the large particles. This

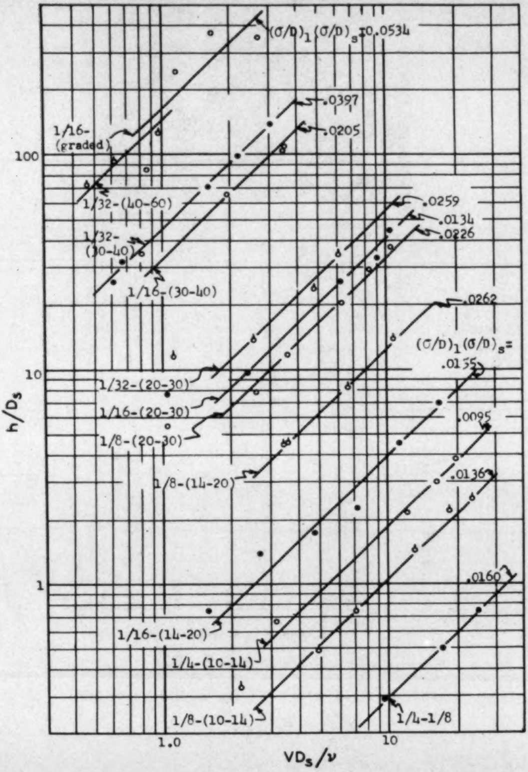


Fig. 4--Head loss parameter as a function of the Reynolds number

resulted in a decrease of head loss at the interface with increasing velocity because of the increase in pore size in the adjacent region as a result of the loss of material. This phenomenon is shown by the curved lines of Figure 6. Previous experiments dealing with the stability of filters have relied on visual inspection to determine whether or not there is movement of the small particles. The technique employed by the investigations reported herein is believed to be more sensitive.

Filter action did not occur if the ratio of the grain size of the filter to that of the filtrate exceeded about five. Criteria for filter action as proposed by this study are

$$\frac{D_{15} \text{ for filter}}{D_{85} \text{ for filtrate}} < 4.1 \qquad \frac{D_{50} \text{ for filter}}{D_{50} \text{ for filtrate}} < 5.3$$

These criteria may be compared with criteria proposed by TERZAGHI [1925], U. S. WATERWAYS EXPERIMENT STATION [1941], U. S. BUREAU OF RECLAMATION [1947], and BERTRAM [1948] which are summarized below:

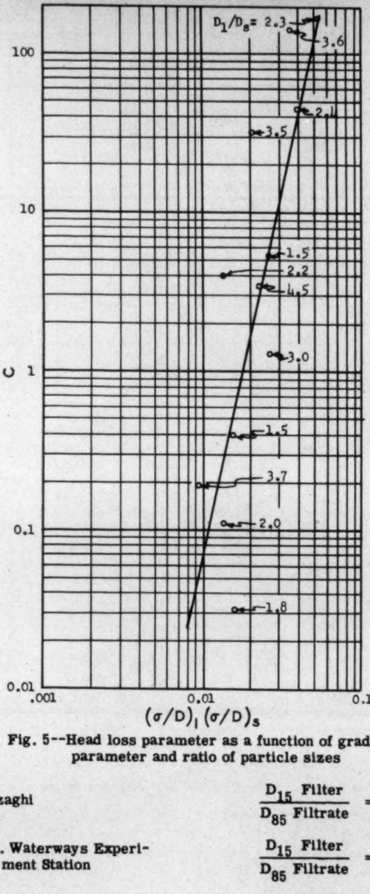


Fig. 5--Head loss parameter as a function of gradation parameter and ratio of particle sizes

Terzaghi $\dfrac{D_{15}\ \text{Filter}}{D_{85}\ \text{Filtrate}} = 4$

U. S. Waterways Experiment Station $\dfrac{D_{15}\ \text{Filter}}{D_{85}\ \text{Filtrate}} = 5$

Bertram $\dfrac{D_{15}\ \text{Filter}}{D_{85}\ \text{Filtrate}} = 9$

U. S. Bureau of Reclamation

Uniform materials $\dfrac{D_{50}\ \text{Filter}}{D_{50}\ \text{Filtrate}} = 5\text{-}10$

Graded materials $\dfrac{D_{50}\ \text{Filter}}{D_{50}\ \text{Filtrate}} = 12\text{-}58$

In the foregoing D_{15} is defined as the diameter of the particle for which 15 pct of the material is finer.

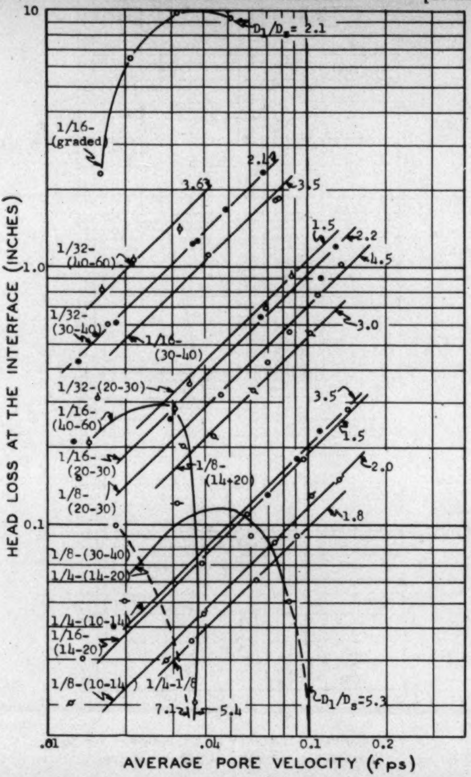


Fig. 6--Variation of head loss with velocity for different ratios of particle sizes

Acknowledgments--This work was carried out [LEATHERWOOD, 1952] under a fellowship made available by the Johnson Well Screen Co. Credit is due Carl Rohwer and Sol D. Resnick for assistance and advice.

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VERTICAL RESOLUTION IN THE NEUTRON METHOD FOR MEASURING SOIL MOISTURE

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(Contribution from the Department of Agronomy, North Carolina Agricultural Experiment Station, and the Department of Physics, North Carolina State College. Published with approval of the Director of Research as Paper No. 483 of the Journal Series.)

Abstract--A source of fast neutrons and a slow neutron detecting device in close proximity have been used to measure the moisture content of soil. The work was done with a 10-mc Ra-Be source and a BF_3-filled counter (2.5×30 cm). Rates varied between 16 and 2 counts per second. The vertical extent of the soil layer contributing 95 pct of the measured counting rate varied from 65 cm with very dry material (4.4 pct water by volume) to 45 cm with saturated material (38 pct water by volume). It has been shown possible, by partial shielding of the counting tube with cadmium foil to increase vertical resolution, at expense of counting rate. This procedure is not very effective, however.

General aspects of the neutron method--The neutron scattering method for measuring soil-moisture content has been introduced only recently into the literature. The principle on which it is based has been well stated by GARDNER and KIRKHAM [1952]. However, an exact description of the process, which would permit prediction of counting rates, is not available and would probably offer singular difficulties in development.

Considerable effort to study the possibilities of the neutron method seems amply justified. The method promises outstanding advantages over existing methods of measuring soil-moisture content. These advantages have been adequately discussed in earlier articles by BELCHER and Others [1950, 1952], and by GARDNER and KIRKHAM [1952]. Briefly, the desirable aspects of the neutron method are: (a) absence of lag or hysteresis; (b) large sample size and, consequently, small standard error; (c) short measuring time with suitable equipment; (d) no disturbance of the soil which is to be studied; (e) no effects of temperature, dissolved materials, or changes of state of the water; (f) response curves are linear in first approximation; and (g) with a particular instrumental setup, calibration appears to differ little between different soils.

Item (b) may, sometimes, be an actual disadvantage and (g) appears still somewhat doubtful. In view of the uncertain and time-consuming calibration which is entailed by electrical conductivity or thermal conductivity methods for measuring soil moisture, (g) commands particular interest. Gardner and Kirkham investigated seven very different soils and found that the relation of counting rate to moisture content could be presented in a single curve for all the soils used. However, there is considerable scatter in their data, attributable to either the counting error, the error of the moisture determination, or to an inherent differential behavior of the different soils. Moreover, Gardner and Kirkham did not show stringently that their soil sample was "effectively infinite." Work of greater accuracy seems required to settle the point.

The present work was mainly concerned with investigating the vertical resolution, that is, the thickness of the layer of soil which significantly determines the counting rate that is observed. Accurate knowledge about the vertical resolution and of the factors which influence it is of obvious interest in evaluating the neutron method as a tool in research and in operations.

Instrumentation and experimental method--The measuring part of the equipment consisted of a 10-mc Ra-Be source, attached to a BF_3 slow neutron-counting tube as shown in Figure 1. (This tube is manufactured by General Electric Co., Model 973784-7G1. Later work showed that a preferable counter was the B_{10}-lined counter made by the same manufacturer, Model 9159777G4.) The strength of the source was approximately 1.5×10^5 n/sec with energies between 2 and 10 mev (average 4.4). (The minimum safe working distance to the source in its lead shield is 65 cm, at which distance the γ-ray dose is 6.25 mr/h and the neutron flux 3 n/sec/cm^2 (maximum permissible neutron flux is 22 n/sec/cm^2). The α- and β-rays are entirely absorbed by the shield. Thus the source constitutes no great hazard, with reasonable precautions.) Partial shielding of the sensitive volume of the counter was accomplished by pushing over the tube a sheath rolled from 1/16 inch metallic cadmium.

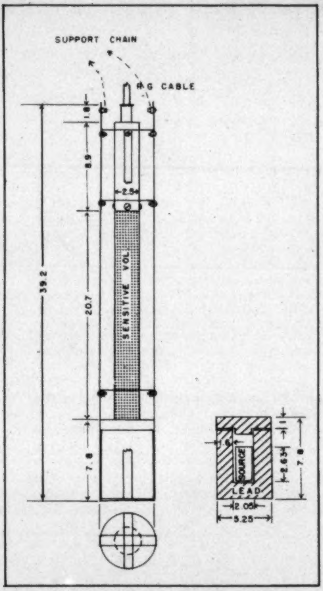

Fig. 1--Source-counter assembly; dimensions in centimeters

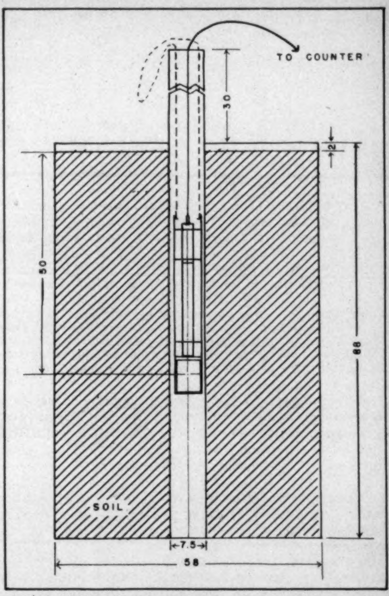

Fig. 2--Barrel with soil, tube, and source-counter assembly; dimensions in centimeters

The counting rate was determined with a conventional scaler (manufactured by Nuclear Instrument and Chemical Corp., Model 162) in the usual manner. Optimum voltage to operate the counter was found to be 1550 v and the discriminator was set to obtain the maximum number of neutron-induced pulses excluding at the same time all gamma ray-induced pulses. "Background" was negligibly small, about 0.01 count per second.

Before each experiment a standard run was made in a defined volume of water. The coefficient of variation of the standard counts was 0.3 pct as compared with a coefficient of variation of 1.2 pct for individual counts. Therefore, it was concluded that no significant variation in the performance of the equipment occurred during the course of the work.

A first set of experiments consisted of having a 55-gallon barrel filled with sand or soil at uniform moisture content. The latter as well as the bulk density was carefully determined throughout the entire barrel. The standard error and coefficient of variation for the moisture content by volume are given in Table 1.

The source-counter assembly was moved inside a thin-walled aluminum pipe, 7.5 cm in diameter, placed centrally in the barrel (Fig. 2) and the counting rate determined at 5-cm intervals over the entire vertical extent of the barrel. In all cases a minimum of 6400 counts were taken, thus giving a standard error of less than two per cent.

The objective of the first set of experiments was to determine the depth below the surface and the height above the bottom at which the maximum counting rate would be attained, as well as the effect of moisture content thereon.

Table 1--Variability of moisture content in containers with sand or soil

Material	Moisture content by volume	Standard error	Coefficient of variation
	pct	pct	pct
Sand	38.0	0.15	0.4
Soil	28.4	0.37	1.3
Soil	17.6	0.21	1.2
Sand	9.0	0.16[a]	1.8
Sand	4.4	0.08	1.8

[a] Based on incomplete data.

In a second experiment, bags filled with wet sawdust (moisture content approximately 100 pct by volume) were stacked around the barrel, in order to determine whether or not the barrel was larger in the horizontal direction than the "sample" being measured.

With the purpose of modifying the vertical resolution, the relation between counting rate and the position of the source-counter assembly was again determined, but now with a varying amount of the sensitive volume shielded with cadmium, as described above.

Description and discussion of results--The effect of the moisture content on the vertical extent of the layer determining the counting rate is shown in Figure 3. In this figure, as well as Figure 4, the size of the circles indicating the individual data is a measure for the variability. The radius of the circle is the pertaining standard error and, therefore, the diameter is approximately the least significant difference at the five per cent level of probability. The points where the counting rate was more than 2.5 pct different from the plateau value were designated at the limits of the plateau. In Figure 3, these limits are indicated by short vertical lines and the numerical value of five per cent of the plateau value is indicated by a bracket in the center of the plateau. The resolution was then calculated as the height of the barrel minus the length of the plateau. Figure 5 shows the effect of moisture content on resolution in centimeters.

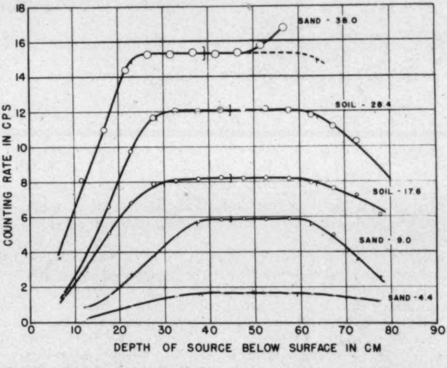

Fig. 3--Counting rate by depth for varying uniform-moisture content

Vertical resolution is markedly dependent upon moisture content in the neutron method. Partially, this is an advantage since the inherent variability of moisture content in natural soils is known to increase with decreasing moisture content. But, on the other hand, one will often desire greater resolution so that variations of moisture content on a smaller scale are ascertained.

It was found that the presence of bags with wet sawdust around the barrel did not increase counting rate appreciably when the moisture content was 28.4 pct by volume and only by six per

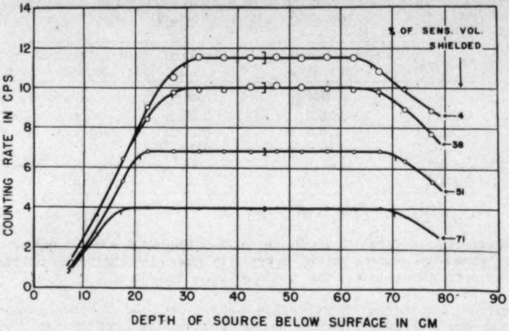

Fig. 4--Counting rate by depth for various degrees of partial shielding

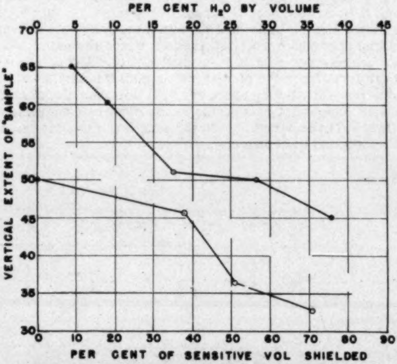

Fig. 5--Resolution in centimeters as determined by moisture content and by partial shielding of the counter

cent at a moisture content of nine per cent by volume. Thus, it was concluded that the experimental method represented substantially conditions of infinite dimensions in the horizontal direction.

The experiment in which the effect of partial shielding of the counter on vertical resolution was examined was done with soil at 28.4 pct moisture content by volume. The data are shown in Figure 4 in which it appears that increasing the fraction of the counter that is shielded causes the plateau to be longer. This is more clearly brought out in Figure 5 in which the vertical resolution, computed as shown above, is seen to increase with increased shielding. Partial shielding may prove advantageous in certain applications but it is done at expense of counting rate. This, in turn, means less accuracy or longer counting time.

The results given above are qualitatively in agreement with the theory of neutron scattering (compare with Gardner and Kirkham). In pure water the average distance that a fast neutron will travel before it is slowed and may be detected is about 14 cm. Resolution should be of the same order of magnitude. The average slowing-down length is roughly inversely proportional to the density of the moderator; and, assuming that the solid constituents of the soil would contribute nothing to the slowing process, one may approximately compute values. For a moisture content of 40 pct by volume the order of magnitude of resolution would then be 35 cm; and for a moisture content of ten per cent, 140 cm. Experimentally, we found values of 45 and 65 cm respectively, showing that at least the correct order of magnitude may be approximated.

Little can be done to modify the consequences of the intrinsic properties of fast neutrons. Measuring slow neutron flux in a smaller volume closer to the source may improve resolution. The data obtained with cadmium shielding would show this. But the overall counting rate is much decreased, in part as a result of the "poisoning" of the system by inserting the cadmium cylinder. Gardner and Kirkham suggest collimation of the source, but a practical manner for doing so appears unavailable.

Some practical considerations--The neutron method appears to be fairly simple in practical application. Equipment that is now available performs dependably and is not excessively expensive in comparison with equipment used in other methods for soil-moisture measurement. A portable rate meter to be used instead of the conventional scaler is now under development [see Soil Science, v. 77, p. 339, 1954].

With the equipment used in the present work, accuracy of about three per cent of the values of moisture content by volume would require maximally three minutes of counting time. Such accuracy is probably often in excess of what is required for practical applications. Vertical resolution appears to be smaller than would be suitable for most work. Partial shielding of the counter has been shown here to be not very effective. The use of shorter counters may be more helpful.

A particular difficulty arises when measurement is desired of the moisture content of superficial layers. BELCHER and Others [1952] reported that in such cases one might merely place source and counter side by side on the soil surface. Preliminary investigations done by the authors confirmed the practicability of this method of measurement and showed the thickness of the surface sample to be about 20 cm. This magnitude depends on the equipment which is used.

The general calibration curve is given in Figure 6. The lower part of the curve appears somewhat uncertain. For moisture contents below five per cent, the barrel is not "infinite" in the horizontal direction and the counting rate, therefore, is too low. The relationship is approximately linear as others have found before [BELCHER and Others, 1950, 1952; SPINKS and Others, 1951; LANE and Others, 1953; GARDNER and KIRKHAM, 1952], and the two different materials used do not appear to give points belonging to different curves. The present investigations are not exhaustive enough, however, to be conclusive in regard to the calibration curve being universal.

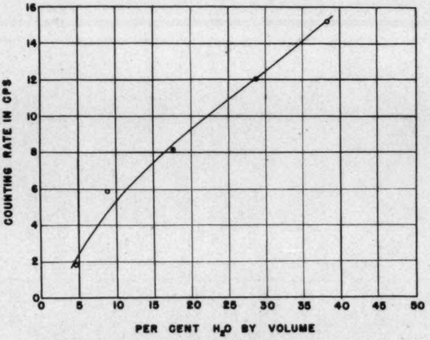

Fig. 6--Counting rate as determined by moisture content; open circles for sand, dots for soil

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MEASUREMENTS OF CUMULATIVE EVAPORATION FROM BARE SOIL

F. J. Veihmeyer and F. A. Brooks

Abstract--Careful measurements were made of evaporation of soil water during 1921 in California at Davis, Delhi, Mountain View, and Whittier. The soil surface was kept free of vegetation and no rain fell for periods of eight to 12 weeks. Analyses of the records indicate that an average curve of evaporation loss against time may be useful for situations where more exact data are not available. Other studies of soil in tanks reveal that, after the first week, the evaporation rate from bare soil without a water table is extremely slow. For a period of 1547 days during which rain was excluded, the average evaporation rate was 0.00236 inch/day. When water tables were maintained at depths between 0.5 and 5.0 ft it was found that the evaporation loss from uncropped soils with high water table was not directly proportional to the depth from the soil surface to the water table.

The main problem in generalizing soil-moisture observations is that of setting the zero date after flood irrigation for the time when the excess surface water has evaporated and the soil surface reaches field capacity, and which marks the start of evaporation from the interstices of the soil. These zero dates have now been estimated for the soil moisture measurements made at Davis, Delhi, Mountain View, and Whittier, California [VEIHMEYER, 1927]. These dates have reasonable reliability because it was possible to compare observed water content of the uppermost layer of the soil with its known field capacity. Then because little difference was found between the cultivated and uncultivated plots these two classes were averaged together. The data for the four locations are given in Table 1.

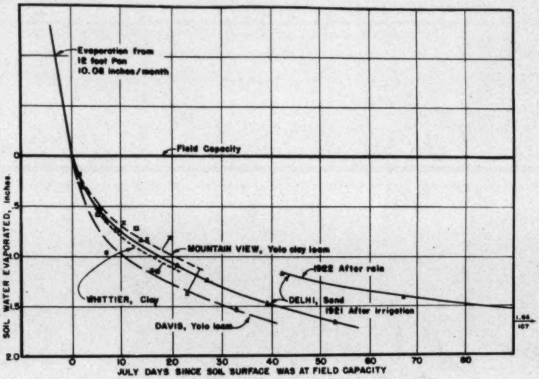

Fig. 1--Cumulative evaporation loss from bare-soil surface corrected for starting at the time the surface reached field capacity, and for July rates for evaporation

Table 1--Average evaporation for cultivated and uncultivated plots; zero dates for end of surface saturation

Date of observation	Equivalent July days since surface at field capacity[a]	Average moisture content, first 3 ft	Average cumulative moisture loss
		inch	inch
1921		Delhi, California	
July 7[b]	. . .	. . .	. . .
9	0	3.48	0.00
11	2	3.16	0.31
16	7	2.83	0.64
23	14	2.64	0.83
30	21	2.38	1.10
Aug. 6	27	2.23	1.24
20	39	2.00	1.48
Sep. 9	53	1.82	1.66
1922			
May 9[c]	0	3.06	0.00
June 30	42	1.90	1.17
July 24	67	1.66	1.40
Sep. 8	107	1.40	1.66
1921		Whittier, California	
July 15[b]	. . .	. . .	. . .
21	0	9.78	0.00
28	5	9.20	0.58
Aug. 4	9	9.04	0.74
11	13	9.06	0.72
18	17	8.63	1.15
1921		Davis, California	
Aug. 2[b]	. . .	. . .	. . .
3	. . .	11.52	. . .
5	. . .	10.14	. . .
6	0	(9.98)	0.00
8	2	9.69	0.29
15	7	9.01	0.97
26	16	8.84	1.14
Sep. 23	33	8.44	1.54
1921		Mountain View, California	
June 26[b]	. . .	. . .	. . .
28	0	(5.68)	0.00
30	2	5.50	0.18
July 7	6	5.17	0.51
14	10.5	5.02	0.66
21	15	4.84	0.84
28	19.5	4.86	0.82
Aug. 4	23.5	4.30	1.38

[a] See Table 2 for method of correcting observed intervals to equivalent July days.

[b] Irrigated on date indicated.

[c] Rain preceding date indicated.

At the time the soil moisture tests were made there was no demand for interpretation in terms of latent heat requirements nor for the use of the summer evaporation data for other times of year. Evaporation rates from a standard water surface would serve to evaluate the energy exchange rates approximately and there are records of evaporation pan rates at all four stations at later dates. Only three evaporation records reported by the State Division of Water Resources [YOUNG, 1947] span the dates of these field tests, and these have been used to transfer the later, local, observed pan-evaporation rates to the 1921 time of field-evaporation measurements. Then all were reduced by using Young's comparison tests made at Fullerton, California, to the equivalent 12-ft diameter pan rates as shown in Table 2. For the comparison of the four field stations and to correct for lower evaporation rate in September, it seemed best to reinterpret the actual number of days between observations to the number of July days required for equal pan evaporation at Delhi (where the most complete data were obtained). This basic month has an evaporation of 10.08 inches as from a 12-ft diameter pan three feet deep. Such arbitrary correction is properly based on insolation and normal convection but may be slightly in error in neglecting the different relative frequency of diurnal cycles which are a factor promoting vapor exchange [RICHARDS, 1952, p. 333].

Table 2--Monthly evaporation in inches from 12-ft diameter tank three feet deep, and monthly per cents relative to the evaporation at Delhi in July, 1921

Station	Year	Item	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Delhi	1921[a]	Evap.	0.73	0.94	1.64	4.75	5.37	7.97	10.08	8.49	5.50	2.73	1.23	0.63
		Pct.	7	9	16	47	53	79	100	84	54	27	12	6
	1922[b]	Evap.	0.61	1.00	2.16	4.91	7.06	9.36	10.69	9.10	6.08	3.06	1.11	0.19
		Pct.	6	10	21	49	70	93	106	90	60	30	11	2
Davis	1921[c]	Evap.	0.75	1.54	2.66	3.94	6.12	8.46	9.21	7.73	5.63	4.01	1.66	0.81
		Pct.	7	15	26	39	61	84	91	77	56	40	16	8
Mountain View	1921[d]	Evap.	0.86	0.51	1.91	3.80	4.98	5.76	6.52	5.36	3.34	1.61	1.03	0.45
		Pct.	9	5	19	38	49	57	65	53	33	16	10	4
Whittier	1921[e]	Evap.	1.08	2.30	3.92	4.43	3.82	5.23	6.90	5.56	4.12	2.54	1.71	1.13
		Pct.	11	23	39	44	38	52	68	55	41	25	17	11

[a] Estimated from 1922-1928 average pan evaporation corrected by ratio of pan evaporation at Oakdale, 1921, to Oakdale, 1922-1928 [YOUNG, 1948, p. 128].

[b] Observed April to December; estimated January to March from 1923-1928 average [YOUNG, 1948, p. 58].

[c] Estimate based on average pan evaporation 1926-1945 corrected by ratio of mean monthly Fahrenheit temperatures in 1921 to those for 1926-1945 [YOUNG, 1948, p. 56].

[d] Estimate from 1922 pan evaporation corrected by Davis ratio 1921:1922.

[e] Estimated from 1930-1931 average pan evaporation corrected by ratio of average Chula Vista and Yuma (mesa) pan evaporation rates for 1921 compared to the 1930-1931 average [YOUNG, 1948, pp. 45, 193, and 195].

Figure 1 shows the four curves which are remarkably consistent considering the wide variation in soil character and geographical location. Deviations of the measurements at all stations are within plus or minus 20 pct of the Delhi curve except for two of the 24 points. Therefore, if this curve is taken as the mean for all four cases, the cumulative evaporation loss is seen to be about 0.2 inch in one day, 0.5 in 5 days, 1.0 in 17 days, and 1.5 in 43 July days. The longest record after the water was applied was obtained at Delhi in 1922. The curve for this year does not fall on the one for the previous year, but shows similarity. It also shows that the evaporation rate approaches zero after a long period.

To determine the natural evaporation from a bare soil over a period of five years without rain, a weighable tank containing Yolo clay loam was initially irrigated very carefully so that the soil was wet only down to six inches from the tank bottom. The tank was 48 inches deep and the soil surface area exposed to evaporation was 3.01 sq ft. The soil in the tank was left undisturbed except weeds which started to grow were pulled. The tank was covered during rains to eliminate any addition of water after the initial irrigation, but the cover was removed immediately after each rain. The tank was observed for 1547 days and the loss of water was equivalent to 3.65 inches for the entire period. This is an average loss of 0.00236 inch/day. About one-third of the total loss from the tank occurred by the end of the first month. The soil in this tank was not reduced to the permanent wilting percentage except in the top foot. The slow loss of moisture after the rapid drying of the surface soil is shown in Figure 2 which gives the loss for the first year after the water was applied to the soil.

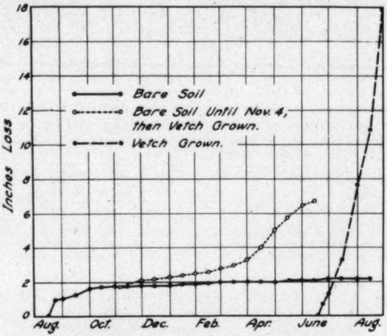

Fig. 2--Comparative cumulative losses of water from bare and cropped soil

A comparison of the evaporation of water from the bare soil and the losses by transpiration and evaporation from a cropped soil is also shown in Figure 2. These data are taken from a previous report [VEIHMEYER, 1927], but are presented here again to illustrate the great difference between losses of moisture from bare and cropped soils. The losses from the tank exposed to evaporation for the long period of time with bare undisturbed soil are shown by the solid line. A similar tank had bare undisturbed soil for 80 days after irrigation and then, on November 4, vetch was planted. Since the top four inches of soil were too dry at this time to germinate the seed, just enough water (about three pounds) was placed around the seeds to allow them to start growing. The transpiration from these plants grown during the relatively cool part of the year is shown by the dashed line in Figure 2. The plants matured and were removed on June 15. On June 20 this tank was irrigated and vetch was planted again. This was irrigated several times. Growing during the hot part of the year, these plants used 18.87 inches of water as shown in Figure 2. The vetch plants in this tank just covered the area of the soil surface in the tank. The conversion of pounds lost to inches depth, therefore, is justified.

To investigate the evaporation from bare soil with a free water surface at various depths, a series of tanks was installed in a trench at Davis and arranged so that they could be lifted and weighed. Each tank was equipped with a water-level regulator operating on the Mariotte principle so that a water table was maintained at a desired level. The depth to the water surface maintained in the tanks, the number used, the dimensions, depth of soil, and the kind of soil used with approximate weight are given in Table 3.

The tanks were placed in trenches so that the soil surface was at about the general ground level in the vicinity of the trenches. The space between the tanks and the trench was closed by means of metal covers so that the sides of the tanks were not exposed to the Sun. The soil was placed in the tank several years before the experiments were started. The soil was well settled and had about the same apparent specific gravity as the soil in place in the field.

The experiment was conducted from May, 1935, through September, 1939. During 1935, 1936, and up to November, 1937, the tanks were exposed to the rain; after that, they were covered when it began to rain, but the covers were removed shortly after the rains ceased. The time the tanks were covered was a very small portion of the total season. Corrections were made for the amount of water added to the tanks by rain in calculating the evaporation losses. In some cases, during the first three years of the experiment, the rain was so heavy that the tanks attached to the sides to supply water to the soil tanks overflowed and the records for these short periods of time were

Table 3--Equipment used to study the evaporation from bare soils with a free water surface at various depths from the surface of the soil

Depth of free water surface from soil surface	Number of tanks used in tests	Dimensions of tanks		Area of exposed soil surface	Approximate weight of soil in tanks	Type of soil
		Diameter	Approximate depth of soil			
ft		inch	inch	sq in	lb	
0.5	8	25	30	490.87	825	Yolo fine sandy loam
1.0	5	25	30	490.87	825	Yolo fine sandy loam
1.5	4	28	60	615.74	1850	Yolo silt loam
2.0	5	28	60	615.74	1850	Yolo silt loam
3.0	8	28	60	615.74	1850	Yolo silt loam
5.0	8	28	60	615.74	1850	Yolo silt loam

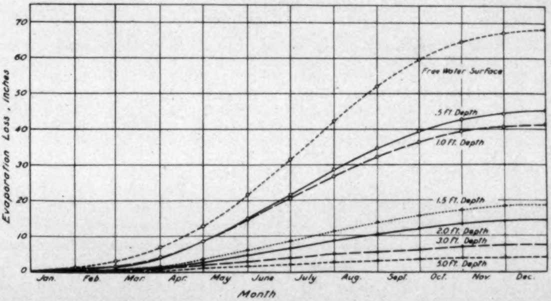

Fig. 3--Cumulative evaporation from bare soil in tanks with water tables maintained at the depths from the surface of the soil as indicated; the evaporation from free water surface is the record from a Weather Bureau pan four feet in diameter and ten inches deep

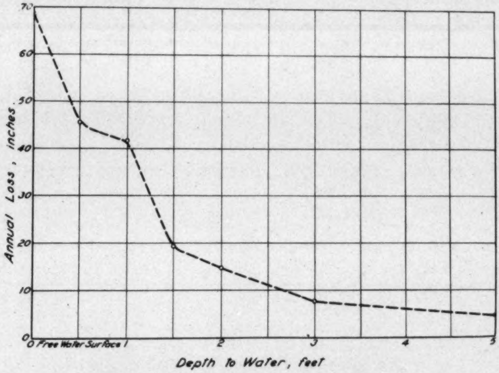

Fig. 4--Annual evaporation from soils with the water table at different depths from the surface lost. The records for water lost by evaporation from the tanks expressed in equivalent depths in inches are given in Table 4 and Figure 3. The variations in evaporation as a function of depth and with each set of tanks for the five years of observation are given in Table 5. Only one month, August, was selected. The variations for this month are typical of those for the other months of the year. The mean annual losses for the various depths of water table are given in Figure 4. The evaporation from a class-A U. S. Weather Bureau pan is also plotted for comparison. This pan is four feet in diameter and ten inches deep. It is clearly evident that a water table one foot below the bare surface has a pronounced effect and the evaporation rates do not bear a linear relation to depth of the water table from the soil surface. The shape of the curve in Figure 4, therefore, is markedly different from those given by HOUK [1930].

Table 4--Evaporation from a free water surface (U. S. Weather Bureau pan) and from bare soils in tanks with water standing at various depths from the soil surface, equivalent depths in inches; mean values, 1935-1939

Depth of water table	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Total
ft													
Pan[a]	1.37	1.90	3.60	5.80	8.75	9.51	10.55	9.66	7.53	4.81	2.56	1.29	67.33
0.5	0.65	1.05	2.41	4.68	6.30	6.66	6.97	6.20	4.69	3.38	1.60	0.96	45.55
1.0	0.49	1.26	2.51	4.53	6.08	6.10	5.82	5.73	4.22	3.03	1.30	0.70	41.75
1.5	0.39	0.46	0.78	2.21	2.48	2.52	2.65	2.41	1.97	1.67	1.30	0.26	19.10
2.0	0.25	0.38	0.57	1.63	1.83	2.04	1.95	2.04	1.39	1.54	0.92	0.21	14.75
3.0	0.23	0.40	0.38	0.98	0.86	0.94	0.87	0.82	0.77	0.85	0.48	0.15	7.73
5.0	0.12	0.13	0.20	0.65	0.47	0.48	0.49	0.45	0.43	0.44	0.15	0.17	4.18

[a] U. S. Weather Bureau pan, as noted in title.

Table 5--Evaporation from bare soils in tanks with water standing at various depths from the soil surface, equivalent depths in inches; month of August

Year	Value	Water table at					
		0.5 ft	1.0 ft	1.5 ft	2.0 ft	3.0 ft	5.0 ft
1935	Mean	8.05±0.064[a]	7.50±0.385[a]	2.48±0.234[a]	3.35±0.171[a]	1.01±0.057[a]	0.58±0.054[a]
	Maximum	8.20	8.14	1.98	4.17	1.35	0.86
	Minimum	7.80	6.03	3.02	2.71	0.90	0.46
1936	Mean	6.20±0.075	5.88±0.140	2.97±0.420	2.46±0.183	0.95±0.377	0.56±0.035
	Maximum	6.62	6.35	4.00	2.94	1.10	0.69
	Minimum	5.95	5.62	2.18	1.87	0.80	0.41
1937	Mean	6.20±0.149	5.86±0.098	2.45±0.313	1.56±0.006	0.71±0.042	0.45±0.017
	Maximum	6.70	6.05	3.30	1.77	0.86	0.50
	Minimum	5.38	5.56	1.85	1.48	0.41	0.34
1938	Mean	5.50±0.291	4.96±0.149	2.09±0.196	1.38±0.096	0.73±0.079	0.30±0.044
	Maximum	7.70	5.35	2.61	1.71	0.89	0.49
	Minimum	5.05	4.59	1.89	1.21	0.54	0.22
1939	Mean	5.07±0.084	4.45±0.316	2.06±0.265	1.43±0.110	0.68±0.037	0.35±0.051
	Maximum	5.41	5.07	2.74	1.61	0.87	0.58
	Minimum	4.89	3.27	1.57	1.08	0.57	0.09

[a] Standard error.

When the soil-evaporation curves in Figures 1 to 3 are translated into evaporative cooling, one inch represents an absorption of more than 5200 Btu/ft^2. The average July insolation rate on a horizontal surface in Fresno is 2600 Btu/ft^2; hence the water-surface evaporation of 0.3 inch/day utilizes 60 pct of the whole day's incident solar energy. On the second July day of soil-moisture evaporation the 0.1 inch vaporized takes 20 pct of the incident solar energy. After a dry summer the energy use for evaporation from bare soil is negligible. If, however, a water table is within one foot of the bare surface, the soil evaporation loss is comparable to the transpiration loss for an irrigated crop.

Acknowledgment--Grateful acknowledgment is made for the assistance of Roy Wray and M. R. Huberty in making the measurements of evaporation from the waterlogged tanks.

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A METHOD FOR DETERMINING THE MINIMUM DURATION OF WATERSHED EXPERIMENTS

Jacob L. Kovner and Thomas C. Evans

Abstract--A simple graphic solution is described for approximating the length of time required to detect significant differences between treatments on experimental watersheds.

Introduction--An increasing awareness of the importance of water to local and national welfare has prompted numerous small watershed studies of the relationship between streamflow and forest cover. The experimental methods in use are quite varied, but in general resemble the familiar pattern of comparing some element of streamflow on treated watersheds with that of untreated or control watersheds.

One very simple and popular design, used extensively at the Coweeta Hydrologic Laboratory in North Carolina, employs two watersheds with similar streamflow characteristics. Ordinarily this also means similar elevations, aspects, climates, and soil complexes. Prior to treatment, measurements of streamflow (such as yield, storm peaks, sedimentation, and quality) are collected on both watersheds for a number of years known as the period of calibration. These data are used to establish the regression of a streamflow characteristic of one watershed upon the other. By this method, variation not associated with treatment (for example, differences such as temperature and rainfall for different years) is placed under statistical control in the subsequent test of difference in streamflow characteristics between the calibration and treatment periods. Following calibration, one of the watersheds is treated according to the specifications of some land-use or forest management practice, and measurements of streamflow continued until the investigator is satisfied that an adequate test of treatment effects has been made.

Analysis of the two sets of data, one set for each period, is by the method of covariance [SNEDECOR, 1946], which supplies a significance test of the adjusted difference due to treatment. WILM [1944, 1949] has demonstrated the method, using an example of annual discharge or yield from a control and treated watershed. In addition, by making the logical and simple assumption that equal samples (for example, streamflow records of equal duration) are drawn from each of the two periods, he has arrived at a method of successive approximations for estimating how long the calibration period should be.

A more general solution can be derived for the length of both the calibration and treatment periods. Under the conditions of the test it need not be assumed that the periods are of equal length. On some watershed studies, calibration data have been accumulated for relatively long periods. Here, of course, treatment may be applied at once, and it is of interest to the investigator to anticipate how long the post-treatment observation should be continued. It is also frequently necessary to estimate appropriate time intervals for spacing successive treatments, as in the case of removing a forest cover in a series of partial cuts. Furthermore, when the effect of the treatment is short-lived, longer periods of observation tend to mask the effect. Again, when funds, personnel, and the physical resource in land are limited, estimates of the length of post-treatment period are powerful aids to long-time planning and assignment of project priorities.

It is the purpose of this paper to propose a method of estimating the minimum length of the treatment period, and of a whole watershed experiment, and to arrive at a simplication of WILM's [1949] technique by substituting a graphic solution for the more laborious method of successive approximations.

Method of analysis--With a slight modification to admit periods of unequal length, the equation for the square of a mean difference after WILM [1949] may be written

$$d^2 = s_{y.x}^2 \, F \, [1/n_1 + 1/n_2 + (\overline{X}_1 - \overline{X}_2)^2/S_x^2] \qquad (1)$$

where S_x^2 is the within treatment pooled sum of squares of the independent variable, n_1 and n_2 are the number of observations in the calibration and treatment periods, respectively, $s_{y \cdot x}^2$ is the experimental variance developed from residual deviations from regression, and F is the variance ratio.

Some simplification of (1) is possible by substituting the approximation

$$(\bar{X}_1 - \bar{X}_2)^2 \simeq F\ sx^2\ (1/n_1 + 1/n_2)$$

and remembering that

$$sx^2 = Sx^2/n_1 + n_2 - 2$$

By appropriate substitution and rearrangement (1) resolves to

$$\frac{s_{y \cdot x}^2}{d^2} = \frac{n_1 n_2}{n_1 + n_2}\left[\frac{1}{F\,(1 + \frac{F}{n_1 + n_2 - 2})}\right] \ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

wherein F has degrees of freedom equal to unity and $n_1 + n_2 - 3$.

Because it leads to better graphical presentation, the form in (2) is preferred to the more common $d/s_{y \cdot x}$.

With n_1 and an estimate of $s_{y \cdot x}^2$ both taken from the calibration data, and an experience value for the smallest worthwhile difference, d, (2) might be solved for n_2 by the method of successive approximations. A simpler solution is possible by graphics. Figure 1 shows the relation (2) as a family of curves for values of n_2 with F at a probability level of 0.05. Sample calculations for deriving plotting points are shown in Table 1, which contains the solution for $n_2 = 5$. Similar computations at $P = 0.01$ would complete the usual working range of significance.

Table 1--Sample computations for $s_{y \cdot x}^2/d^2$ for $n_2 = 5$, $P = 0.05$

n_1	$n_1 + n_2 - 2$	$n_1 + n_2 - 3$ (D. F.)	F	$F\,(1 + \frac{F}{n_1 + n_2 - 2})$	$\frac{n_1 n_2}{n_1 + n_2}$	$\frac{s_{y \cdot x}^2}{d^2}$
3	6	5	6.61	13.8920	1.8750	0.1350
4	7	6	5.99	11.1156	2.2222	0.1999
5	8	7	5.59	9.4963	2.5000	0.2633
6	9	8	5.32	8.4647	2.7273	0.3222
7	10	9	5.12	7.7414	2.9167	0.3768
8	11	10	4.96	7.1965	3.0769	0.4276
9	12	11	4.84	6.7920	3.2143	0.4733
10	13	12	4.75	6.4857	3.3333	0.5140
11	14	13	4.67	6.2279	3.4375	0.5520
12	15	14	4.60	6.0108	3.5294	0.5872
13	16	15	4.54	5.8285	3.6111	0.6196
14	17	16	4.49	5.6758	3.6842	0.6492
15	18	17	4.45	5.5500	3.7500	0.6756
16	19	18	4.41	5.4336	3.8095	0.7011
17	20	19	4.38	5.3392	3.8636	0.7237
18	21	20	4.35	5.2509	3.9130	0.7451
19	22	21	4.32	5.1684	3.9583	0.7660
20	23	22	4.30	5.1041	4.0000	0.7837

With these curves, the estimated minimum length of the post-treatment period is readily solved if n_1, $s_{y \cdot x}^2$, and d are known, for it is necessary only to compute $s_{y \cdot x}^2/d^2$, and enter the curves at the coordinate value determined by n_1 and $s_{y \cdot x}^2/d^2$. The curve nearest the coordinate point is the required estimate of n_2.

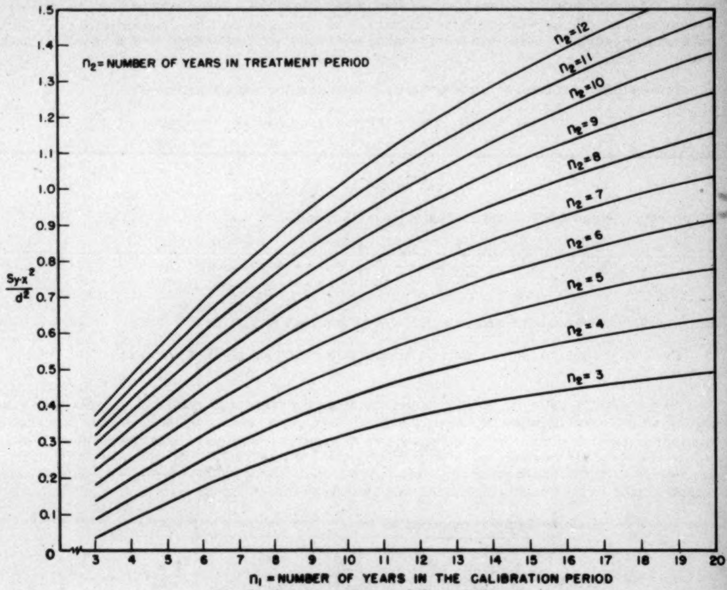

Fig. 1--Graphic solution of the equation

$$\frac{s_{y\cdot x}^2}{d^2} = \frac{n_1 n_2}{n_1 + n_2}\left[\frac{1}{F\left(1 + \frac{F}{n_1 + n_2 - 2}\right)}\right]$$

for the purpose of estimating length of calibration and treatment periods

Of course, of the three quantities, only n_1 is known precisely before the treatment is installed. The variance $s_{y\cdot x}^2$ is an estimate of the pooled residual variances around regression to be obtained after the post-treatment period, and d is generally predetermined by practical considerations based on experience [WILM, 1949].

Examples of the method--The data in Table 2, showing annual water yields, were obtained from records at the Coweeta Hydrologic Laboratory. Data are given for both a calibration and treatment period so as to permit an estimate of n_2 and an empirical check of the estimate.

The error variance for the calibration period $s_{y\cdot x}^2$ is 2.389; n_1 is 12. An experience value for the smallest worthwhile difference, d, may be taken as five per cent of the mean yield for the calibration period of the watershed subsequently chosen for treatment. Then $0.05 \times 28.916 = 1.446$ area-inches, which provides

$$s_{y\cdot x}^2/d^2 = 2.389/2.090 = 1.143$$

Entering Figure 1 with $n_1 = 12$ and $s_{y\cdot x}^2/d^2 = 1.143$, the curve nearest this point is $n_2 = 12$. It is estimated, therefore, that the treatment would have to run 12 years in order that a difference of 1.446 area-inches may be judged significant at a probability level of 0.05.

Table 2--Annual discharge from Watersheds A and B (discharge in area-inches)

Calibration period 1934-1945	Watershed		Treatment period 1946-1952	Watershed	
	A	B		A	B
1934	33.89	35.53	1946	12.17	16.01
1935	13.16	15.38	1947	15.03	20.83
1936	12.20	12.96	1948	25.50	28.07
1937	22.57	23.58	1949	46.76	45.88
1938	32.87	33.82	1950	38.33	39.00
1939	27.89	31.64	1951	30.48	31.58
1940	16.73	17.75	1952	51.87	52.43
1941	35.36	34.99			
1942	20.82	23.74			
1943	30.71	31.35			
1944	53.38	49.13			
1945	38.79	37.12			
Total	338.37	346.99		220.14	233.80
Average	28.198	28.916		31.449	33.400

Similar computations at other values of d (Table 3) show that if the experiment must be concluded within, say five years, then a treatment effect less than 2.00 area-inches cannot be expected to appear significant. If, on the other hand, the smallest worthwhile difference could be increased to ten per cent, a three-year test is likely to detect a difference of approximately 3.0 area-inches.

Table 3--Solution for length of treatment period

Precision as per cent of mean discharge on Watershed B	Least significant difference, in area-inches, d	d^2	$s_{y \cdot x}^2/d^2$	n_1 years	n_2 years
5	1.446	2.091	1.143	12	12
6	1.735	3.010	0.794	12	7
8	2.313	5.350	0.447	12	4
10	2.892	8.364	0.286	12	3

By way of verification, an analysis of covariance was run on the treatment data on Table 2, testing for significance of the adjusted mean yields. The analysis was applied first at the end of the three-year treatment period 1946-1948, and then successively for the 1946-1949, 1946-1950, 1946-1951, and 1946-1952 treatment periods, as would be done in actual practice. The analysis shows that it was necessary to run the treatment for seven years, 1946-1952, in order to show a real difference of 1.66 area-inches due to treatment. This is 5.7 pct of the calibration mean yield on Watershed B. Referring to Table 3, we find that the estimate of $n_2 = 7$ years for a least significant difference equal to six per cent of this mean is in agreement with actual results.

The curves can also be used to determine how long the calibration period should be when we have an estimate of $s_{y.x}^2$, however obtained. This is an alternate method to that proposed by WILM [1949] using successive approximations. In this case it is only necessary to take equal samples, that is $n_1 = n_2$. Thus $s_{y.x}^2/d^2$ is calculated as previously. Then we enter the vertical scale at this value and move horizontally along this ordinate until that curve is intersected such that $n_1 = n_2$.

As a numerical example, the third line of Table 3 shows d = 2.313 area-inches and $s_{y.x}^2/d^2 = 0.447$; we find that along the 0.447 ordinate the condition that $n_1 = n_2$ is satisfied for the value 6.5 years. Note that we can interpolate between the parametric curves. Therefore, seven years is probably a good estimate of how long the calibration period should be.

It is interesting to see how the results obtained by this method compare with those given by WILM [1949, p. 275]. In his example we find that $s_{y.x}^2/d^2 = 0.266$. Reference to our Figure 1 shows directly that $n_1 = n_2 = 5$, that is, the calibration period is estimated at five years. This agrees precisely with the solution by Wilm. It will be found that the other examples by Wilm can be solved by the use of Figure 1.

Finally, the researcher might want to specify the number of samples in the two periods and have some information regarding the precision or the least significant difference which could be detected. This can be done by entering the curves with values of n_1 and n_2 and reading the corresponding value of $s_{y.x}^2/d^2$; if an estimate of the numerator, $s_{y.x}^2$, is available, d^2 and d are readily calculated.

For example, let us take $n_1 = 12$ and $n_2 = 3$. Then from Figure 1 the corresponding ordinate value $s_{y.x}^2/d^2$ is 0.37. Using $s_{y.x}^2 = 2.39$ from Table 2, $d^2 = 2.39/0.37 = 6.46$, or $\underline{d} = 2.54$ area-inches.

Summary--The investigator is frequently presented with the practical problem of determining the number of observations required to show a significant difference between two means if the difference is greater than a fixed amount and some estimate of the variance is known. In hydrologic research on streamflow with experimental watersheds, a similar problem arises. A simple graphic method has been presented which provides the following information: (1) Length of the treatment period following a known extended calibration period; (2) length of the calibration period in advance; and (3) the smallest difference due to treatment which can be detected as significant at a chosen probability level, when the length of two periods has been assumed. This method may be applied in other problems where, in effect, we are comparing two or more regression lines.

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ON ATTENUATION OF WAVES PRODUCED IN VISCO-ELASTIC MATERIALS

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Abstract--A solution to the problem of wave motion produced when a pressure pulse is applied to the interior surface of a spherical cavity in a visco-elastic medium is obtained. Comparison with the elastic case indicates that viscosity significantly reduces the amplitude of the displacement in the vicinity of the wave front and decreases the velocity of propagation of the wave.

In the addendum, a pressure-time pulse defined by a function of the form $P(t) = P\gamma t \exp(-\zeta t)$ is applied to the cavity wall and a solution of the differential equations of motion is obtained using the theory developed in the main body of the paper. Since all values of the parameter ζ are admissible, pressure-time pulses of arbitrary form may be represented by superposing individual pulses of the above form corresponding to different values of ζ.

Terminology--The following symbols are used.

r, α, θ = spherical coordinates defined by: the surfaces of spheres, r = constant; radial planes perpendicular to some plane through the origin, α = constant; and right circular cones with vertices at the origin, θ = constant
σ = stress
ϵ = strain
G = elastic modulus of rigidity
λ = elastic Lame constant defined by $E\nu/(1+\nu)(1-2\nu)$ where E is the modulus of elasticity and ν is Poisson's ratio
K = coefficient of viscosity analogous to G
μ = coefficient of viscosity analogous to λ
Δ = cubical dilatation
u = displacement
t = time variable
δ = cavity radius
ρ = density
a = acceleration
∇^2 = Laplacian

Introduction--As a preliminary step leading to the investigation of the effect of seismic waves on structures, it appears advisable to determine the attenuation of such waves. MORRIS [1950] suggests that an explosion causes a diverging wave in which the stresses near the source greatly exceed the strength of the material. However, the wave attenuates such that, at some distance from the origin, the stresses will be equal to the material strength.

SHARPE [1942] obtained a solution for the problem of wave motion produced by an explosive pressure pulse in a spherical cavity located in an infinite elastic medium. His solution essentially idealizes the effect of an explosion by assuming that a spherical surface exists where the stresses are just equal to the strength of the material.

Other investigators have also treated wave motion in elastic media. However, it is thought that a visco-elastic representation of the materials of the Earth is more realistic. Consequently, it is of interest to investigate wave attenuation in a visco-elastic medium. Such an investigation (considering only first order viscous effects) is presented in this paper. The equation of motion for a visco-elastic material is written in terms of a displacement potential. A solution to the resulting differential equation is determined and generalized over the disturbance wave frequency by using a Fourier integral representation for the pressure pulse. Evaluation of this solution by contour integration results in the displacement potential and hence the radial displacement as a function of position and time.

Two solutions are obtained and compared with each other and a solution for a perfectly elastic material. One of these results from the assumption that only first-order viscous effects are considered. The other assumes only first-order viscous effects everywhere except at the surface of the cavity where perfect elasticity is assumed.

Analysis--A formal statement of the problem under consideration may be made as follows: Given a spherical cavity of radius δ within an infinite, homogeneous, isotropic, visco-elastic medium; to find the wave motion resulting from the application of a pressure pulse to the interior surface of the cavity.

The visco-elastic medium is here assumed to be a "Kelvin solid" [REINER, 1949]. Its rheological model shown in Figure 1 indicates that the strains of the viscous and elastic elements are equal and that the stress of the complete configuration is the sum of the stresses in the individual elements.

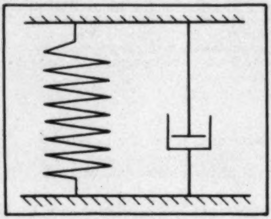

Fig. 1--Rheological model for the Kelvin solid

The solution of the problem formally stated above follows an analysis substantially equivalent to that used by SHARPE [1942] for a similar problem relating to an elastic medium. Accordingly, a solution is sought here which vanishes at infinity, and satisfies the boundary condition requiring the stress in the medium at the surface of the cavity to be at all times equal to the pressure applied to the interior surface. It is assumed that the pressure at the surface of the cavity is everywhere the same. This idealizes the problem and essentially limits the interior surface to displacements corresponding to a zero order spherical harmonic.

The stress-strain relationships for the Kelvin solid may be obtained by superposition of the stresses for the elastic and the viscous element. For the elastic element [SOKOLNIKOFF, 1946]

$$\left.\begin{aligned}
\sigma_{rr} &= 2G\epsilon_{rr} + \lambda\Delta \\
\sigma_{\theta\theta} &= 2G\epsilon_{\theta\theta} + \lambda\Delta \\
\sigma_{\alpha\alpha} &= 2G\epsilon_{\alpha\alpha} + \lambda\Delta \\
\sigma_{\alpha r} &= \sigma_{r\alpha} = 2G\epsilon_{r\alpha} \\
\sigma_{\theta r} &= \sigma_{r\theta} = 2G\epsilon_{r\theta} \\
\sigma_{\theta\alpha} &= \sigma_{\alpha\theta} = 2G\epsilon_{\alpha\theta}
\end{aligned}\right\} \quad \cdots\cdots\cdots\cdots (1)$$

For the viscous element (by analogy with the elastic element)

$$\left.\begin{aligned}
\sigma_{rr} &= 2\mu\dot{\epsilon}_{rr} + K\dot{\Delta} \\
\sigma_{\theta\theta} &= 2\mu\dot{\epsilon}_{\theta\theta} + K\dot{\Delta} \\
\sigma_{\alpha\alpha} &= 2\mu\dot{\epsilon}_{\alpha\alpha} + K\dot{\Delta} \\
\sigma_{\alpha r} &= \sigma_{r\alpha} = 2\mu\dot{\epsilon}_{r\alpha} \\
\sigma_{\theta r} &= \sigma_{r\theta} = 2\mu\dot{\epsilon}_{r\theta} \\
\sigma_{\theta\alpha} &= \sigma_{\alpha\theta} = 2\mu\dot{\epsilon}_{\alpha\theta}
\end{aligned}\right\} \quad \cdots\cdots\cdots\cdots (2)$$

where $\cdot$ indicates $\partial/\partial t$. Therefore, superposition of (1) and (2) gives

$$\left.\begin{aligned}
\sigma_{rr} &= 2G\epsilon_{rr} + 2\mu\dot{\epsilon}_{rr} + \lambda\Delta + K\dot{\Delta} \\
\sigma_{\theta\theta} &= 2G\epsilon_{\theta\theta} + 2\mu\dot{\epsilon}_{\theta\theta} + \lambda\Delta + K\dot{\Delta} \\
\sigma_{\alpha\alpha} &= 2G\epsilon_{\alpha\alpha} + 2\mu\dot{\epsilon}_{\alpha\alpha} + \lambda\Delta + K\dot{\Delta} \\
\sigma_{\alpha r} &= \sigma_{r\alpha} = 2G\epsilon_{r\alpha} + 2\mu\dot{\epsilon}_{r\alpha} \\
\sigma_{\theta r} &= \sigma_{r\theta} = 2G\epsilon_{r\theta} + 2\mu\dot{\epsilon}_{r\theta} \\
\sigma_{\theta\alpha} &= \sigma_{\alpha\theta} = 2G\epsilon_{\alpha\theta} + 2\mu\dot{\epsilon}_{\alpha\theta}
\end{aligned}\right\} \quad \cdots\cdots\cdots\cdots (3)$$

The strain components and equations of motion for infinitesimal strain theory are given in SOKOLNIKOFF [1946]. They are

$$\left.\begin{aligned}
\epsilon_{rr} &= \partial u_r/\partial r \\
\epsilon_{\theta\theta} &= (1/r)\,(\partial u_\theta/\partial\theta) + u_r/r \\
\epsilon_{\alpha\alpha} &= (1/r \sin\theta)\,(\partial u_\alpha/\partial\alpha) + u_r/r + u_\theta \cot\theta/r \\
\epsilon_{\alpha r} = \epsilon_{r\alpha} &= 0.5\,[(1/r \sin\theta)\,(\partial u_r/\partial\alpha) - u_\alpha/r + \partial u_\theta/\partial r] \\
\epsilon_{\theta r} = \epsilon_{r\theta} &= 0.5\,[(1/r)\,(\partial u_r/\partial\theta) - u_\theta/r + \partial u_\theta/\partial r] \\
\epsilon_{\theta\alpha} = \epsilon_{\alpha\theta} &= 0.5\,[(1/r)\,(\partial u_\alpha/\partial\theta) - u_\alpha \cot\theta/r + (1/r \sin\theta)\,(\partial u_\theta/\partial\alpha)]
\end{aligned}\right\} \quad \ldots\ldots \quad (4)$$

where the displacement subscripts indicate displacement components.

$$\begin{aligned}
\rho a_r &= \partial\sigma_{rr}/\partial r + (1/r\sin\theta)(\partial\sigma_{r\alpha}/\partial\alpha) + (1/r)(\partial\sigma_{r\theta}/\partial\theta) + (1/r)[2\sigma_{rr} - \sigma_{\alpha\alpha} - \sigma_{\theta\theta} + \sigma_{r\theta}\cot\theta] \\
\rho a &= \partial\sigma_{r\alpha}/\partial r + (1/r \sin\theta)\,(\partial\sigma_{\alpha\alpha}/\partial\alpha) + (1/r)\,(\partial\sigma_{\alpha\theta}/\partial\theta) + (1/r)\,[3\sigma_{r\alpha} + 2\sigma_{\alpha\theta} \cot\theta] \qquad (5) \\
\rho a_\theta &= \partial\sigma_{r\theta}/\partial r + (1/r \sin\theta)\,(\partial\sigma_{\alpha\theta}/\partial\alpha) + (1/r)\,[3\sigma_{r\theta} + (\sigma_{\theta\theta} - \sigma_{\alpha\alpha}) \cot\theta] + (1/r)\,(\partial\sigma_{\theta\theta}/\partial\theta)
\end{aligned}$$

where the acceleration subscripts indicate acceleration direction.

Using (3) and (4), the equations of motion, (5) may be written in terms of displacement as follows

$$\begin{aligned}
\rho a_r = {} & (\partial/\partial r)\left\{[\lambda + K\,(\partial/\partial t)]\,\Delta + [2G + 2\mu\,(\partial/\partial t)]\,(\partial u_r/\partial r)\right\} \\
& + (1/r)\,(\partial/\partial\theta)\left\{[G + \mu\,(\partial/\partial t)]\,[(1/r)\,(\partial u_r/\partial\theta) - u_\theta/r + \partial u_\theta/\partial r]\right\} \\
& + (1/r \sin\theta)\,(\partial/\partial\theta)\left\{[G + K\,(\partial/\partial t)]\,[(1/r \sin\theta)\,(\partial u_r/\partial\alpha) - u_\alpha/r + \partial u_\alpha/\partial r]\right\} \\
& + (1/r)\left\{[2G + 2\mu\,(\partial/\partial t)][2\,(\partial u_r/\partial r) - 2u_r/r - (1/r\sin\theta)\,(\partial u_\alpha/\partial\alpha) - u_\theta\cot\theta/r\right. \\
& \left. - (1/r)\,(\partial u_\theta/\partial\theta)]\right\} + (\cot\theta/r)\left\{[G + \mu\,(\partial/\partial t)]\,[(1/r)\,(\partial u_r/\partial\theta) - u_\theta/r + \partial u_\theta/\partial r]\right\} \quad \ldots\ldots\ldots \quad (6a)
\end{aligned}$$

$$\begin{aligned}
\rho a_\alpha = {} & (\partial/\partial r)\left\{[G + \mu\,(\partial/\partial t)]\,[(1/r \sin\theta)\,(\partial u_r/\partial\alpha) - u_\alpha/r + \partial u_\alpha/\partial r]\right\} \\
& + (1/r)\,(\partial/\partial\theta)\left\{[G + \mu(\partial/\partial t)][(1/r)(\partial u_\alpha/\partial\theta) - u_\alpha\cot\theta/r + (1/r\sin\theta)(\partial u_\theta/\partial\alpha)]\right\} \\
& + (1/r\sin\theta)(\partial/\partial\alpha)\left\{[\lambda + K(\partial/\partial t)]\,\Delta + [2G + 2\mu\,(\partial/\partial t)][(1/r\sin\theta)(\partial u_\alpha/\partial\alpha) + u_r/r\right. \\
& \left. + u_\theta \cot\theta/r]\right\} + (1/r)\left\{[3G + 3\mu\,(\partial/\partial t)]\,[(1/r \sin\theta)\,(\partial u_r/\partial\alpha) - u_\alpha/r + \partial u_\alpha/\partial r]\right\} \\
& + (\cot\theta/r)\left\{[2G + 2\mu\,(\partial/\partial t)]\,[(1/r)\,(\partial u_\alpha/\partial\theta) - u_\alpha \cot\theta/r + (1/r \sin\theta)\,(\partial u_\theta/\partial\alpha)]\right\} \quad \ldots\ldots \quad (6b)
\end{aligned}$$

$$\begin{aligned}
\rho a_\theta = {} & (\partial/\partial r)\left\{[G + \mu\,(\partial/\partial t)]\,[(1/r)\,(\partial u_\theta/\partial\theta) - u_\theta/r + \partial u_\theta/\partial r]\right\} \\
& + (1/r)\,(\partial/\partial\theta)\left\{[\lambda + K(\partial/\partial t)]\,\Delta + [2G + 2\mu(\partial/\partial t)]\,[(1/r)\,(\partial u_\theta/\partial\theta) + u_r/r]\right\} \\
& + (1/r\sin\theta)(\partial/\partial\alpha)\left\{[G + \mu(\partial/\partial t)][(1/r)(\partial u_\alpha/\partial\theta) - u_\alpha\cot\theta/r + (1/r\sin\theta)(\partial u_\theta/\partial\alpha)]\right\} \\
& + (1/r)\left\{[3G + 3\mu\,(\partial/\partial t)]\,[(1/r)\,(\partial u_r/\partial\theta) - u_\theta/r + \partial u_\theta/\partial r]\right\} \\
& + (\cot\theta/r)\left\{[2G + 2\mu\,(\partial/\partial t)][(1/r)(\partial u_\theta/\partial\theta) - (1/r\sin\theta)(\partial u_\alpha/\partial\alpha) - u_\theta\cot\theta/r]\right\} \quad \ldots\ldots\ldots \quad (6c)
\end{aligned}$$

Introducing the expression for cubical dilatation [SOKOLNIKOFF, 1946], assuming spherical symmetry (that is, u_θ, u_α and changes with respect to θ and α are zero) and dropping the subscript r, (6) reduces to

$$\rho\,(\partial^2 u/\partial t^2) = [(\lambda + 2G) + (K + 2\mu)\,(\partial/\partial t)][(\partial^2 u/\partial r^2) + (2/r)\,(\partial u/\partial r) - 2u/r^2] \quad \ldots\ldots \quad (7)$$

This equation governs any dilatational motion of the medium and may be written

$$\rho\,(\partial^2 u/\partial t^2) = [(\lambda + 2G) + (K + 2\mu)\,(\partial/\partial t)]\,(\partial/\partial r)\,(\partial u/\partial r + 2u/r) \quad \ldots\ldots\ldots\ldots \quad (8)$$

On introducing the displacement potential ϕ defined by

$$u = \partial\phi/\partial r \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

Eq. (8) becomes

$$\rho (\partial^2/\partial t^2)(\partial\phi/\partial r) = [(\lambda + 2G) + (K + 2\mu)(\partial/\partial t)](\partial/\partial r)[(\partial^2\phi/\partial r^2) + (2/r)(\partial\phi/\partial r)]$$

or, on integrating with respect to r

$$\partial^2(r\phi)/\partial t^2 = c^2[\partial^2(r\phi)/\partial r^2] + k^2(\partial/\partial t)[\partial^2(r\phi)/\partial r^2 + (2/r)(\partial\phi/\partial r)] \quad \ldots\ldots\ldots (10)$$

where

$$c^2 = (\lambda + 2G)/\rho$$

$$k^2 = (K + 2\mu)/\rho$$

A solution of (10) is the displacement potential for a dilatational disturbance in the medium. The appropriate boundary condition in terms of an arbitrary, time dependent pressure function P (t) may be written

$$-\sigma_{rr}\Big]_{r=\delta} = P(t)$$

or

$$-[c^2\rho(\partial u/\partial r) + k^2\rho(\partial/\partial t)(\partial u/\partial r) + 2\lambda u/r + (2K/r)(\partial u/\partial t)]_{r=\delta} = P(t)$$

or, representing P(t) as a Fourier integral

$$-[c^2\rho(\partial u/\partial r) + k^2\rho(\partial/\partial t)(\partial u/\partial r) + 2\lambda u/r + (2K/r)(\partial u/\partial t)]_{r=\delta}$$

$$= (1/2\pi)\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \exp[in(\xi - t)]\, P(\xi)\, dn\, d\xi \quad \ldots\ldots\ldots\ldots\ldots (11)$$

The variables in (10) are separable. Thus, if a wave solution of the form $\phi = f_n(r)\exp(-int)$ is sought, a solution of (10) may be written

$$\phi = (1/r)\exp[-\gamma(r - \delta)]\exp\left\{-in[t - \beta(r - \delta)]\right\} \quad \ldots\ldots\ldots\ldots\ldots (12)$$

where

$$\gamma = \sqrt{(n^2\sqrt{c^4 + n^2k^4} - n^2c^2)/2(c^4 + n^2k^4)}$$

$$\beta = \sqrt{(\sqrt{c^4 + n^2k^4} + c^2)/2(c^4 + n^2k^4)}$$

n = a real arbitrary constant

The right hand side of (12) multiplied by any functions independent of r and t is still a solution. Consequently,

$$\phi = (1/2\pi r)\, N(n)\, P(\xi)\exp[-\gamma(r - \delta)]\exp\left\{-in[t - \beta(r - \delta) - \xi]\right\}$$

is also a solution. Likewise, an infinite sum of such solutions will also be a solution. Therefore

$$\phi = (1/2\pi r)\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} N(n)\, P(\xi)\exp[-\gamma(r - \delta)]\exp\left\{-in[t - \beta(r - \delta) - \xi]\right\} dn\, d\xi \quad \ldots (13)$$

is still a solution.

Upon substitution of (9) and (13) into (11), the boundary condition becomes

$$\begin{aligned}(1/2\pi)\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} N(n)\,\llbracket\, & c^2\rho n^2\beta/\delta + i2c^2\rho n\beta\gamma/\delta - c^2\rho\gamma^2/\delta + i2c^2\rho n\beta/\delta^2 \\ & - 2c^2\rho\gamma/\delta^2 - 2c^2\rho/\delta^3 - ik^2\rho n^3\beta^2/\delta + 2k^2\rho n^2\beta\gamma/\delta \\ & + ik^2\rho n\gamma^2/\delta + 2k^2\rho n^2\beta/\delta^2 + i2k^2\rho n\gamma/\delta^2 + i2k^2\rho n/\delta^3 \\ & - 2\lambda n\beta/\delta^2 + 2\lambda\gamma/\delta^2 + 2\lambda/\delta^3 - 2kn^2\beta/\delta^2 - i2kn\gamma/\delta^2 \\ & - i2kn/c^3 \,\rrbracket\, P(\xi)\exp[-in(t-\xi)]\,dn\,d\xi \\ & = (1/2\pi)\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\exp[-in(t-\xi)]\,P(\xi)\,dn\,d\xi \quad \ldots\ldots\ldots\ldots\ldots\ldots (14)\end{aligned}$$

This identity in t is satisfied if

$$N(n) = \llbracket\ \rrbracket^{-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (15)$$

Using this expression for N(n) in (13) determines, in principle at least, ϕ and hence the displacement u. However, it does not appear possible to perform the integration in its present form. Therefore, the following simplifying assumptions are made: (1) Assume that $(k^2/\delta c) << 1$ and that powers of $(k^2/\delta c)$ may be neglected in comparison with one. (2) Assume that $(k^2/\delta c)^2$ is so small that very little contribution to the evaluation of the summation over n in (13) is made by the terms in which $n^2\delta^2/c^2$ becomes large enough to make $(n^2\delta^2/c^2)(k^2/\delta c)^2$ of the order of one. Thus

$$\gamma = n^2k^2/2c^3 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (16)$$

$$\beta = 1/c \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (17)$$

since $2\gamma n\,\beta = n^3k^2/c^4$.

Using the aforementioned assumptions and, in addition, assuming that $\lambda = G$ [SHARPE, 1942], the expression for N(n) reduces to

$$N(n) = \llbracket(\rho/\delta)n^2\left\{1-(2/3)(k^2/\delta c)+4[(\mu/\rho)/\delta c]\right\} + i(4Gn/c\delta^2)\left\{1+3[(\mu/\rho)/\delta c]\right\} - (4G/\delta^3)\rrbracket^{-1} \quad ..(18)$$

It is noted that the basic assumption made in obtaining (18) is small damping, namely, $(k^2/\delta c) << 1$. This assumption implies neglecting viscosity effects beyond the first order.

Eq. (18) may be written

$$N(n) = (\delta/\rho)\llbracket n^2\left\{1-(2/3)(k^2/\delta c)+4[(\mu/\rho)/\delta c]\right\} + in\left\{1+3[(\mu/\rho)/\delta c]\right\} - 4G/\delta^2\rho\rrbracket^{-1}$$

or, factoring the quadratic in the brackets

$$N(n) = (\delta/\rho)\left\{[n+(iA+B)][n+(iA-B)]\right\}^{-1} \quad \ldots\ldots\ldots\ldots\ldots (19)$$

where

$$A = 2c\left\{1+3[(\mu/\rho)/\delta c]\right\}/3\delta\left\{1-(2/3)(k^2/\delta c)+4[(\mu/\rho)/\delta c]\right\}$$

$$B = 2c\sqrt{2}\ \sqrt{1+3[(\mu/\rho)/\delta c]-4.5[(\mu/\rho)/\delta c]^2-(k^2/\delta c)}\,/3\delta\left\{1-(2/3)(k^2/\delta c)+4[(\mu/\rho)/\delta c]\right\}$$

It is noted that A and B are positive since $[(\mu/\rho)/\delta c] < (k^2/\delta c) << 1$.

Substituting (19) in (13)

$$\phi = (\delta/2\pi\rho r)\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{[P(\xi)\exp[-\gamma(r-\delta)]\exp\left\{-in[t-\beta(r-\delta)-\xi]\right\}}{[n+(iA+B)][n+(iA-B)]}\,dn\,d\xi \quad ..(20)$$

This expression for the displacement potential satisfies both (10) and the boundary condition for the assumed first order damping approximation. It is the solution to the problem for an arbitrary pressure function at the surface of the cavity.

In evaluating (20) for a pressure pulse at the surface of the cavity, the applied pressure is assumed as

$$\left.\begin{array}{ll} P(t) = P_0 \exp(-\zeta t) & t \geqq 0 \\ P(t) = 0 & t < 0 \end{array}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (21)$$

Then, upon completion of the integration of (20), ζ is allowed to approach zero. (This procedure leads to a solution which satisfies the original differential equations of motion.) This essentially allows the applied pressure to take on the form of a pulse.

Using (21) in (20) and carrying out the ξ integration

$$\phi = -(iP_0\delta/2\pi\rho r)\int_{-\infty}^{\infty} \frac{\exp[-\gamma(r-\delta)]\exp\left\{-in[t-\beta(r-\delta)]\right\}}{(n+i\zeta)[n+(iA+B)][n+(iA-B)]}\, dn \quad \ldots\ldots\ldots (22)$$

The integral can be evaluated by the theorem of residues using the contour shown in Figure 2 as the path of integration.

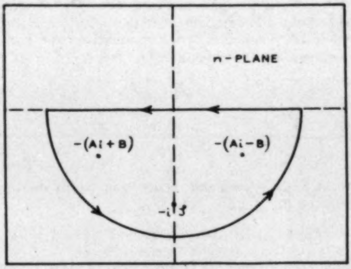

Fig. 2--Integration contour

Thus

$$\int_{-\infty}^{\infty} \frac{\exp[-\gamma(r-\delta)]\exp\left\{-in[t-\beta(r-\delta)]\right\}}{(n+i\zeta)[n+(iA+B)][n+(iA-B)]}\, dn$$

$$= \lim_{R\to\infty}\int_{R}^{-R} \frac{\exp[-\gamma(r-\delta)]\exp\left\{-in[t-\beta(r-\delta)]\right\}}{(n+i\zeta)[n+(iA+B)][n+(iA-B)]}\, dn$$

$$+ \lim_{R\to\infty}\int_{-\pi}^{0} \frac{\exp[-\gamma(r-\delta)]\exp\left\{-iR\exp(i\theta)[t-\beta(r-\delta)]\right\}}{[R\exp(i\theta)+i\zeta][R\exp(i\theta)+(iA+B)][R\exp(i\theta)+(iA-B)]}\, R\exp(i\theta)\, d\theta$$

$$= 2\pi i\Sigma \text{ (residues)}$$

but

$$\lim_{R\to\infty}\int_{-\pi}^{0} \frac{\exp[-\gamma(r-\delta)]\exp\left\{-iR\exp(i\theta)[t-\beta(r-\delta)]\right\}}{[R\exp(i\theta)+i\zeta][R\exp(i\theta)+(iA+B)][R\exp(i\theta)+(iA-B)]}\, R\exp(i\theta)\, d\theta = 0$$

Therefore

$$\int_{-\infty}^{\infty} \frac{\exp[-\gamma(r-\delta)]\exp\left\{-in[t-\beta(r-\delta)]\right\}}{(n+i\zeta)[n+(iA+B)][n+(iA-B)]}\,dn = 2\pi i\Sigma\ \text{(residues)}$$

Defining τ as $[t-\beta(r-\delta)]$ and recalling that $\gamma = n^2k^2/2c^3$ and $\beta = 1/c$, the residues are

$$[\text{residue at } n = -i\zeta] = \left\{\exp[-\gamma_1(r-\delta)]\exp(-\zeta\tau)\right\}/[i\zeta+(iA+B)][i\zeta+(iA-B)]$$

where $\gamma_1 = \zeta^2k^2/2c^3$

$$[\text{residue at } n = -(iA+B)] = \left\{\exp[-\gamma_2(r-\delta)]\exp[i(iA+B)\tau]\right\}/[-(iA+B)+i\zeta][-(iA+B)+(iA-B)]$$

where $\gamma_2 = (iA+B)^2k^2/2c^3$

$$[\text{residue at } n = -(iA-B)] = \left\{\exp[-\gamma_3(r-\delta)]\exp[i(iA-B)\tau]\right\}/[-(iA-B)+i\zeta][-(iA-B)+(iA+B)]$$

where $\gamma_3 = (iA-B)^2k^2/2c^3$

Now, as ζ approaches zero, the applied pressure takes the form of a pulse, namely, $P(t) = P_o$ for $t \geqq 0$ and $P(t) = 0$ for $t < 0$. Therefore, after modifying the residues, (22) becomes

$$\phi = P_o\delta/(A^2+B^2)\rho r\left\{-1-[(iA-B)/2B]\exp[-\gamma_2(r-\delta)]\exp[i(iA+B)\tau]\right.$$
$$\left.+[(iA+B)/2B]\exp[-\gamma_3(r-\delta)]\exp[i(iA-B)\tau]\right\}$$

or, on substitution for γ_2, γ_3 and τ and rearranging the terms

$$\phi = P_o\delta/(A^2+B^2)\rho r\left\{-1-[(iA-B)/2B]\exp(D)\exp(iF)+[(iA+B)/2B]\exp(D)\exp(-iF)\right\} \quad \ldots\ldots (23)$$

where

$$D = -A\left\{t-[(1/c)-(k^2/2c^3A)(B^2-A^2)](r-\delta)\right\}$$
$$F = B\left\{t-[(1/c)+(k^2A/c^2)](r-\delta)\right\}$$

Replacing the imaginary exponentials by trigonometric functions, (23) may be written

$$\phi = P_o\delta/(A^2+B^2)\rho r\left\{-1+[\exp(D)/B](A\sin F+B\cos F)\right\}$$

or

$$\phi = P_o\delta/(A^2+B^2)\rho r\left\{-1+(\sqrt{A^2+B^2}/B)\exp(D)\sin[F+\tan^{-1}(B/A)]\right\} \quad \ldots\ldots (24)$$

Accordingly, the displacement in the medium, corresponding to the application of a pressure pulse to the interior surface of the cavity, becomes

$$u = \partial\phi/\partial r = P_o\delta/\rho(A^2+B^2)\left\llbracket(1/r)^2-(1/r)^2(\sqrt{A^2+B^2}/B)\exp(D)\sin[F+\tan^{-1}(B/A)]\right.$$
$$+(1/r)(\sqrt{A^2+B^2}/B)\exp(D)\left\{-B[(1/c)+(k^2A/c^3)]\cos[F+\tan^{-1}(B/A)]\right.$$
$$\left.\left.+A[(1/c)-(k^2/2c^3A)(B^2-A^2)]\sin[F+\tan^{-1}(B/A)]\right\}\right\rrbracket$$

or

$$u = P_o\delta/\rho(A^2+B^2)\left\llbracket(1/r)^2-(1/r)^2(\sqrt{A^2+B^2}/B)\exp(D)\sin[F+\tan^{-1}(B/A)]\right.$$
$$+(1/r)(\sqrt{A^2+B^2}/B)\exp(D)\sqrt{B^2[(1/c)+(k^2A/c^3)]^2+A^2[(1/c)-(k^2/2c^3A)(B^2-A^2)]^2}\,\sin\left\{F\right.$$
$$\left.\left.+\tan^{-1}(B/A)-\tan^{-1}\frac{B[(1/c)+(k^2A/c^3)]}{A[(1/c)-(k^2/2c^3A)(B^2-A^2)]}\right\}\right\rrbracket \quad \ldots\ldots (25)$$

An expression similar to (25) may be obtained using the assumption that viscous damping is zero at the surface of the cavity and of such magnitude that only first order effects need be considered elsewhere. The resulting equation for the displacement is

$$u = P_o \delta/4G \Big\{ (\delta/r)^2 - (\delta/r)^2 \sqrt{3/2}\ \exp(A_1) \sin(B_1 + \tan^{-1} \sqrt{2})$$

$$+ (\sqrt{2/3}/rc) \sqrt{3\delta^2 c^2 + \delta c k^2 + k^4}\ \exp(A_1) \sin\Big[B_1 + \tan^{-1} \sqrt{2} - \tan^{-1} \frac{\sqrt{2}\,(3\delta c + 2k^2)}{(3\delta c - k^2)}\Big]\Big\} \quad . . (26)$$

where

$$A_1 = -(2c/3\delta)\Big\{t - [(3\delta c - k^2)/3\delta c^2]\,(r - \delta)\Big\}$$

$$B_1 = (2\sqrt{2}\,c/3\delta)\Big\{t - [(3\delta c + 2k^2)/3\delta c^2]\,(r - \delta)\Big\}$$

If viscous damping is assumed to be zero (perfect elasticity), (25) and (26) both reduce to

$$u = P_o \delta/4G[(\delta/r)^2 - (\delta/r)^2 \sqrt{3/2}\ \exp(A_2) \sin(B_2 + \tan^{-1}\sqrt{2}) + (\delta/r)\sqrt{2}\ \exp(A_2) \sin B_2] \quad . . (27)$$

where

$$A_2 = -(2c/3\delta)\,[t - (1/c)\,(r - \delta)]$$

$$B_2 = -\sqrt{2}\,A_2$$

From this equation, the wave velocity is seen to be $1/c$ and the frequency $2\sqrt{2}\,c/3\delta$.

Comparing (25), (26), and (27), it is seen that the static displacement in all cases will be the same if $4G = \rho(A^2 + B^2)$ which in turn leads to $(\mu/\rho)/\delta c = k^2/6\delta c$. Consequently, if the static displacement is the same, with or without damping, (an assumption which seems reasonable) the developed theory appears to establish a relationship between the two damping constants K and μ.

Assuming $(\mu/\rho)/\delta c = k^2/6\delta c$, (25) may be written in terms of the dimensionless displacement u/δ, the dimensionless radial distance r/δ, the dimensionless time tc/δ, and the dimensionless coefficient of damping $k^2/\delta c$ as follows

$$u/\delta = P_o/4G \Big[\!\Big[[1/(r/\delta)]^2 - [1/(r/\delta)]^2 (\sqrt{A'^2 + 2B'^2}/\sqrt{2}\,B')\ \exp(D')\ \sin[F' + \tan^{-1}(\sqrt{2}\,B'/A')]$$

$$+ [1/(r/\delta)](2\sqrt{A'^2 + B'^2}/3\sqrt{2}\,B')\sqrt{2B'^2[1 + (2A'/3)(k^2/\delta c)]^2 + A'^2[1 - (1/3A')(2B'^2 - A'^2)(k^2/\delta c)]^2}\ \sin\Big\{F'$$

$$+ \tan^{-1}(\sqrt{2}\,B'/A') - \tan^{-1} \frac{\sqrt{2}\,B'[1 + (2A'/3)(k^2/\delta c)]}{[1 - (1/3A')(2B'^2 - A'^2)(k^2/\delta c)]}\Big\}\Big]\!\Big] \quad . . . . (28)$$

where

$$A' = 1 + 0.5\,(k^2/\delta c)$$

$$B' = [1 - 0.5\,(k^2/\delta c) - (1/8)(k^2/\delta c)^2]^{1/2}$$

$$D' = -(2A'/3)\Big\{(tc/\delta) - [1 - (1/3A')(2B'^2 - A'^2)(k^2/\delta c)]\,[(r/\delta) - 1]\Big\}$$

$$F' = (2\sqrt{2}\,B'/3)\Big\{(tc/\delta) - [1 + (2A'/3)(k^2/\delta c)]\,[(r/\delta) - 1]\Big\}$$

Similarly, (26) becomes

$$u/\delta = P_o/4G \Big[\!\Big[[1/(r/\delta)]^2 - [1/(r/\delta)]^2 \sqrt{3/2}\ \exp(A_1) \sin(B_1 + \tan^{-1}\sqrt{2})$$

$$+ [1/(r/\delta)]\sqrt{2/3}\sqrt{3 + 2(k^2/\delta c) + (k^2/\delta c)^2}\ \exp(A_1) \sin\Big\{B_1 + \tan^{-1}\sqrt{2}$$

$$- \tan^{-1} \frac{\sqrt{2}\,[3 + 2(k^2/\delta c)]}{[3 - (k^2/\delta c)]}\Big\}\Big]\!\Big] \quad . . . . (29)$$

where

$$A_1 = -(2/3)\left\{(tc/\delta) - [1 - (1/3)(k^2/\delta c)][(r/\delta) - 1]\right\}$$

$$B_1 = (2\sqrt{2}/3)\left\{(tc/\delta) - [1 + (2/3)(k^2/\delta c)][(r/\delta) - 1]\right\}$$

and (27) becomes

$$u/\delta = P_0/4G\left\{[1/(r/\delta)]^2 - [1/(r/\delta)]^2\sqrt{3/2}\,\exp(A_2)\sin(B_2 + \tan^{-1}\sqrt{2}) + [1/(r/\delta)]\sqrt{2}\,\exp(A_2)\sin B_2\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (30)$$

where

$$A_2 = -(2/3)\left\{(tc/\delta) - [(r/\delta) - 1]\right\}$$

$$B_2 = -\sqrt{2}\,A_2$$

The solution for small damping throughout the medium, (28), is labeled Solution A; the solution for zero damping at the boundary and small damping elsewhere, (29), is labeled Solution B; the solution for the perfectly elastic medium, (30), is labeled Solution C.

Discussion and conclusions--The theory developed in this paper predicts that the displacement which results from the application of a pressure pulse to the interior of a spherical cavity in an infinite, homogeneous, isotropic, visco-elastic medium (Kelvin solid) is directly proportional to to the pressure and the radius of the cavity and inversely proportional to the rigidity. It is noted from (28), (29), and (30) that the displacement consists of three terms, one of which is non-oscillatory and two of which are oscillatory. The non-oscillatory term, which represents the eventual static displacement of the medium, and the first of the oscillatory terms depend on the distance as $[1/(r/\delta)]^2$. The second oscillatory term depends on the distance as $1/(r/\delta)$. Consequently, the first two terms are negligible for relatively large distances from the origin.

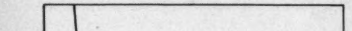

Fig. 3--Relationship of dimensionless displacement to dimensionless radial distance from solutions A, B, and C, for a dimensionless time (tc/δ) of 19 and a dimensionless damping coefficient $(k^2/\delta c)$ of 0.1

The wave form is represented in Figure 3 by plotting the dimensionless displacement u/δ as a function of the dimensionless radial distance r/δ for Solution A, (28), Solution B, (29), and Solution C, (30). It is noted that there is a bump in the curve near the wave front. This bump is essentially a measure of the magnitude of the disturbance which would be transmitted to an object in the path of the wave. The maximum amplitude of this bump is decreased by the presence of damping. Solution A and Solution B both indicate a decrease in this maximum amplitude of approximately 60 pct over Solution C.

The decrease in maximum amplitude near the wave front due to damping should be considered in the design of structures to be situated within the medium. It suggests that initial shocks on structures, due to propagated disturbances, could be significantly reduced by surrounding the structure with a material capable of high damping.

Enlarged plots of the relation of u/δ to r/δ near the wave front, for the two damping conditions considered, are shown in Figure 4. These plots were made assuming a linear variation for u/δ in this region. The wave front is seen to be at an r/δ of 18.791 for Solution A and an r/δ of 18.847 for Solution B.

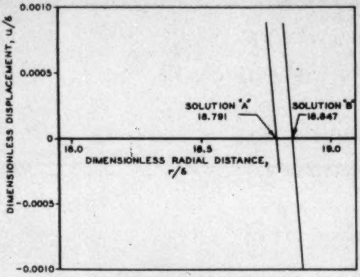

Fig. 4--Enlarged plot of Figure 3 near the wave front

Solutions A and B are seen to be in very close agreement both qualitatively and quantitatively. Therefore, the assumption that the damping effect at the surface of the cavity is negligible appears to be reasonable.

The velocity of the disturbance wave is seen to decrease (Fig. 3) as a result of damping. The wave form, except for a decrease in the displacement amplitudes near the wave front, remains unchanged when damping is considered.

The merits of the theory developed in this paper can, of course, only be decided by an actual check with experimental results. Such a check has not been made.

It should be noted that other cavity surface pressure functions as well as other rheological configurations, in principle at least, can be treated by the theory developed in this paper. An alternate approach could be made if the cavity surface displacement was known as a function of time since the unit solution, (12), could be used directly.

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ADDENDUM

Introduction--The theory developed in this paper readily lends itself to the mathematical determination of the effects produced by the application of pressure-time functions of quite general form to the cavity wall.

Consider a cavity pressure-time function of the form

$$P(t) = P_{\zeta} t \exp(-\zeta t) \quad \ldots\ldots (31)$$

where P_{ζ} = a constant depending on having the dimensions of stress/unit time, and ζ = an arbitrary positive real constant having the dimensions of time.

Theory--Using the pressure function in (31), the following dimensionless expression for displacement may be obtained

$$\begin{aligned} u/\delta = \Big[\!\Big[& [1/(r/\delta)^2] \Big\{ [L/J - 2Q] \exp(-M) - 2 \exp(-D) \sqrt{R^2 + Q^2} \sin [F - \tan^{-1} (Q/R)] \Big\} \\ & + [1/(r/\delta)] \Big\{ [\exp(-M)/J] [1 + \psi(k^2/\delta c)] - \exp(-M) [\psi + (\psi/2)(k^2/\delta c)] [(L/J) - 2Q] \\ & + (4/3) \exp(-D) \sqrt{T} \sqrt{R^2 + Q^2} \sin V \Big\} \Big]\!\Big] (P_{\zeta}\psi/3G) \quad \ldots\ldots (32) \end{aligned}$$

where

$A = 1 + 0.5 (k^2/\delta c)$
$Q = [\psi - (2A/3)]/J^2$
$B = [1 - 0.5 (k^2/\delta c) - (1/8)(k^2/\delta c)^2]^{1/2}$
$\psi = \zeta(\delta/c)$
$J = [-\psi^2 + (4/3)\psi A - (4/9)(A^2 + 2B^2)]$
$R = 3/BJ \sqrt{32}$

$$M = \psi\left\{(tc/\delta) - [1 + 0.5\,\psi(k^2/\delta c)]\,[(r/\delta) - 1]\right\}$$
$$L = \left\{(tc/\delta) - [1 + \psi(k^2/\delta c)]\,[(r/\delta) - 1]\right\}$$
$$D = (2A/3)\left\{(tc/\delta) - [1 - (1/3A)\,(k^2/\delta c)\,(2B^2 - A^2)]\,[(r/\delta) - 1]\right\}$$
$$F = (2\sqrt{2}\,B/3)\left\{(tc/\delta) - [1 + (2A/3)\,(k^2/\delta c)]\,[(r/\delta) - 1]\right\}$$
$$T = 2B^2\,[1 + (2A/3)\,(k^2/\delta c)]^2 + A^2\,[1 - (1/3A)\,(k^2/\delta c)\,(2B^2 - A^2)]^2$$
$$V = \left\{F - \tan^{-1}(Q/R) - \tan^{-1}\frac{B\sqrt{2}\,[1 + (2A/3)\,(k^2/\delta c)]}{A\,[1 - (1/3A)\,(k^2/\delta c)\,(2B^2 - A^2)]}\right\}$$

The theory admits linear combinations of pressure-time functions of the form given in (31) for all numerical values of ζ. Therefore, by adding solutions of the type given in (32), the displacement corresponding to such combinations may be obtained. Furthermore, displacements corresponding to the limiting case of a perfectly elastic material are obtained from this solution by setting k^2 equal to zero.

Discussion and conclusions--The wave forms are computed from (32) for a dimensionless damping coefficient $k^2/\delta c$ of 0.1, $P_\zeta \psi/3G$ set equal to unity, and various values assigned to the dimensionless time parameter tc/δ. These are shown in Figure 5. Figure 6 represents the solution for a perfectly elastic medium obtained by setting $k^2/\delta c$ in (32) equal to zero. Comparison of Figures 5 and 6 shows an amplitude reduction of approximately 55 pct can be attributed to inelasticity and indicates a lower propagation speed in the visco-elastic material. The sharpness of the wave front decreases with time.

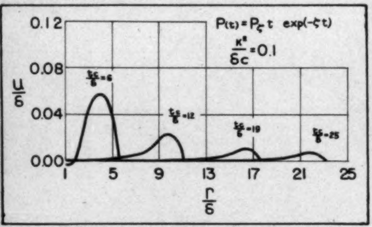

Fig. 5--Relationship of dimensionless displacement to dimensionless radial distance

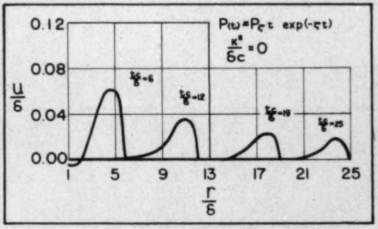

Fig. 6--Relationship of dimensionless displacement to dimensionless radial distance

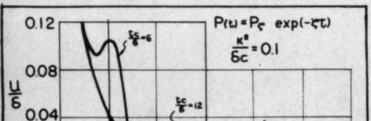

Fig. 7--Relationship of dimensionless displacement to dimensionless radial distance

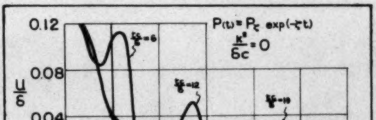

Fig. 8--Relationship of dimensionless displacement to dimensionless radial distance

Figures 7 and 8 are representations of relationships of dimensionless displacements to dimensionless radial distance for Solutions A and C respectively of this paper.

Eq. (32) indicates a selective absorption since attenuation increases exponentially with ζ. In addition the phase angle $\tan^{-1}(Q/R)$ depends on ζ. Thus, one finds both a selective absorption effect depending on the rate of decay due to ζ and a distortion effect due to the phase angle depending on ζ, for linear combinations of displacement solutions corresponding to linear combinations of pressure functions of the form given in (31).

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J. WILLARD GIBBS' VECTOR ANALYSIS IN STRUCTURAL GEOLOGY, PART 2

V. G. Gabriel

Abstract--A vector system is established in a finite hemisphere, and certain pertinent relationships are derived for lines located in the same plane. An example for the solution of field problems with the application of the vector system is given.

Introduction--GABRIEL and PIERSON [1953] have discussed the application of Gibbs' vector analysis to a hemisphere of a unit radius. However, it is believed that certain types of structural problems are more amenable to the use of the vector analysis if a finite hemisphere is used instead of a unit hemisphere.

The problem--Assume a right-hand vector coordinate system $\bar{i}, \bar{j}, \bar{k}$ with point O as the center of the vectorial system (see Fig. 1). Assume also that the system is confined in a hemisphere whose radius is equal to m units, where m is defined by the equation

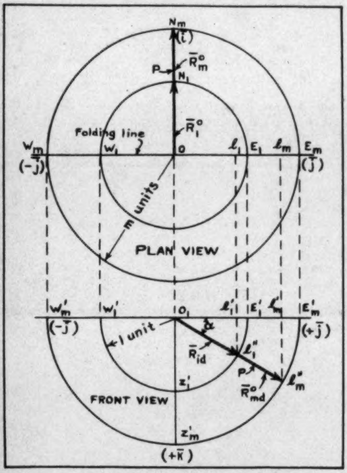

Fig. 1--Plan and front views of two hemispheres whose radii are equal to one unit and m units, respectively

$$0 < m < \infty \text{ . . . . } (1)$$

In plan-view projection (Fig. 1), the hemisphere whose radius is equal to m units is represented by a circle $N_mE_mW_mS_m$. In front-view projection, the northern half of the hemispheres will be represented by the semicircles $O_1E'_mZ'_mW'_m$ and $O_1E'_1Z'_1W'_1$ of radii equal to m units and one unit, respectively. The lines ONm, OEm, and $O_mZ'_m$ are the positive directions of the coordinates $\bar{i}, \bar{j}, \bar{k}$, respectively.

Assume that a plane P, or a formation whose angle of true dip is equal to α degrees, strikes along the line ON_m, that is, the $\bar{i}$ axis. In front-view projection the true dip, that is, α degrees of plane P, will be represented by the angles $E'_mO_1\ell''_m$ and $E'_1O_1\ell''_1$. From the triangles $E'_mO_1\ell''_m$ and $E'_1O_1\ell''_1$ the following relations can be derived

$$\begin{aligned} O_1\ell''_m/O_1\ell''_1 &= O_1E'_m/OE'_1 \\ &= \ell'_m\ell''_m/\ell'_1\ell''_1 \\ &= O_1\ell'_m/O_1\ell'_1 = m/\ell = m \text{ . . . . } (2) \end{aligned}$$

Establishment of pertinent equations related to the same plane--GABRIEL and PIERSON [1953] established the following vectorial and scalar relationships among the straight lines radiating from point O and located in plane P within a unit hemisphere

$$\bar{R}_1 = x'_1\,\bar{i} + y'_1\,\bar{j} + z'_1\,\bar{k} \text{ . . . . } (3a)$$

$$\bar{R}''_1 = x''_1\,\bar{i} + y''_1\,\bar{j} + z''_1\,\bar{k} \text{ . . . . } (3b)$$

. . . .

$$\bar{R}^n_1 = x^n_1\,\bar{i} + y^n_1\,\bar{j} + z^n_1\,\bar{k} \text{ . . . . } (3c)$$

and

$$(x'_1)^2 + (y'_1)^2 + (z'_1)^2 = \dots\dots = (x^n_1)^2 + (y^n_1)^2 + (z^n_1)^2 = 1 \quad (4)$$

where $\bar{R}'_1, \bar{R}''_1, \dots\dots, \bar{R}^n_1$ = unit vectors, $|\bar{R}'_1| = |\bar{R}''_1| = \dots\dots = |\bar{R}^n_1| = 1$, and $x'_1, y'_1, z'_1, x''_1, \dots\dots, z^n_1$ = corresponding scalar values of vector lines $\bar{R}$.

For the same vector coordinate system $\bar{i}, \bar{j}, \bar{k}$, located in a hemisphere whose radius is equal to m units, and from (2), Eq. (3) and (4) are transformed respectively into (see Fig. 1)

$$\bar{R}'_m = x'_m\bar{i} + y'_m\bar{j} + z'_m\bar{k} \quad (5a)$$

$$\bar{R}''_m = x''_m\bar{i} + y''_m\bar{j} + z''_m\bar{k} \quad (5b)$$

$$\bar{R}^n_m = x^n_m\bar{i} + y^n_m\bar{j} + z^n_m\bar{k} \quad (5c)$$

and

$$(x'_m)^2 + (y'_m)^2 + (z'_m)^2 = \dots\dots = (x^n_m)^2 + (y^n_m)^2 + (z^n_m)^2 = m^2 \quad (6)$$

where $\bar{R}'_m, \bar{R}''_m, \dots, \bar{R}^n_m$ = vectors drawn from point O and within the hemisphere of radius m units, $|\bar{R}'_m| = |\bar{R}''_m| = \dots\dots = |\bar{R}^n_m| = m$, and $x'_m, x''_m, \dots, y'_m, y''_m, \dots, z'_m, z''_m, \dots, z^n_m$ corresponding scalar values of vector lines $\bar{R}$.

Designating vectors $\overline{ON}_1, \overline{ON}_m, \overline{O_1\ell''_1}, \overline{O\ell''_m}$ by $\bar{R}^o_1, \bar{R}^o_m, \bar{R}^o_{1d}$, and $\bar{R}^o_{md}$, respectively, we obtain

$$\bar{R}^n_1 = S_1\bar{R}^o_1 + t_1\bar{R}^o_{1d} \quad (7a)$$

$$\bar{R}^n_m = S_m\bar{R}^o_m + t_m\bar{R}^o_{md} \quad (7b)$$

where $\bar{R}^n_1, \bar{R}^n_m$ = vector lines located in plane P and drawn through point O until they pierce the hemispheres of one unit and m unit radii, respectively, and s_1, t_1, s_m, t_m = scalar values of the corresponding vector coordinates.

From (7) we have

$$|\bar{R}^n_1| = 1 = (s_1)^2 + (t_1)^2 \quad (8a)$$

$$|\bar{R}^n_m| = m \quad (8b)$$

$$(s_m)^2 + (t_m)^2 = m^2 \quad (8c)$$

From (8ac)

$$(s_m)^2 + (t_m)^2 = m^2 = (ms_1)^2 + (mt_1)^2 \quad (9)$$

or, from (9)

$$s_m = ms_1 \quad (10a)$$

$$t_m = mt_1 \quad (10b)$$

However, Gabriel and Pierson found that

$$s_1 = \cos\psi_1 \sin\theta_1 \quad (11a)$$

$$t_1 = \cos\psi_1 \sin\theta_1/\cos\alpha = \sin\psi_1/\sin\alpha \quad (11b)$$

where ψ_1 = angle of apparent dip, α = angle of true dip, and θ_1 = angle between the directions of the true and apparent dips. By substituting (11) into (10) we have

$$s_m = m(\cos\psi_1 \sin\theta_1) \quad (12a)$$

$$t_m = m(\cos\psi_1 \cos\theta_1/\cos\alpha) = m\sin\psi_1/\sin\alpha \quad (12b)$$

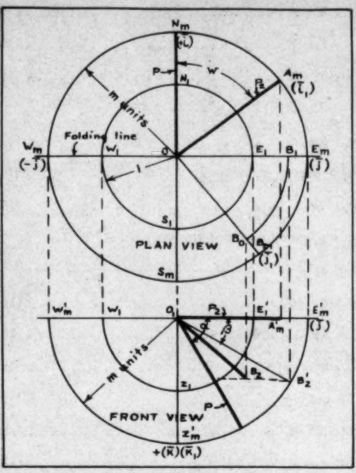
N_m
$(\bar{i})$
P
N_1
W
A_m
$(\bar{i}_1)$
β_2
m units
Folding line
W_m
$(-\bar{j})$
W_1
O
E_1
B_1
E_m
$(\bar{j})$
1
S_1
PLAN VIEW
B_0
B_2
$(\bar{j}_1)$
S_m
W'_m
W_1
O_1
P_2
E'_1
E'_m
$(\bar{j})$
α
β
A'_m
m units
B_2
B'_2
Z_1
P
FRONT VIEW
Z'_m
$+(\bar{k})(\bar{k}_1)$

Fig. 2--Plan and front views of two hemispheres and the planes P and P_2 whose angles of true dip are α and β degrees, respectively

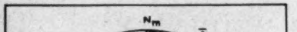
N_m
$(\bar{i})$
$\bar{i}_2$
$\bar{j}_1$
$\bar{j}_2$
B
$\bar{X}_1$
E
F_1
F_0
400 COS 45°
$\bar{i}_1$
85°
$\bar{R}$
$\bar{T}$
F_1^o
W_m
C
A
Folding line
E_m
$(\bar{j})$
500 FT.
m=563.6'
PLAN VIEW
S_m
W'_m
B_1
F'_1
400 COS 45°
A_1
E'_m
$(-\bar{j})$
$(+\bar{j})$
45°
m=563.6'
400 SIN 45°
F'_2
FRONT VIEW
Z'_m
$(\bar{k}_2),(\bar{k}),(\bar{k}_1)$

Fig. 3--Plan and front views of a hemisphere whose radius is equal to m (563.6 ft), for solution of problem

Vectorial relationship of plans different in true strikes and dips--Assume that in addition to plane P, whose true dip is equal to α degrees east and whose true strike is the line ON_m, we have a second plane P_2, whose true strike is the line OA_m and the true dip is equal to β degrees east (see Fig. 2), located in a vertical plane passing through OB_m of the plan view. In front view the lines $O_1A'_m$ and O_1B_2 are the strike and dip projections, respectively, where the points B_o and B_2 are the projections of a line located in plane P_2 and piercing the m hemisphere, let us say, at point B. Assume a new coordinate system $\bar{i}_1$ (line OA_m), $\bar{j}_1$ (line OB_m), and $\bar{k}_1$ (line $O_1Z'_m$) and designating

$$\overline{OA}_m = \overline{R}^{O'}{}_m \quad \ldots\ldots\ldots\ldots (13a)$$

$$\overline{OB} = \overline{R}^{O'}{}_{md} \quad \ldots\ldots\ldots\ldots (13b)$$

$$\overline{O_1Z'}_m = \bar{k}_1 = \bar{k} \quad \ldots\ldots\ldots (13c)$$

where the lines OB_o and O_1B_2 are the projection of the line OB piercing the m hemisphere at point B.

Because the magnitude of vectors $\overline{OA}_m$ and $\overline{R}^{O'}{}_{md}$ is m, from (2), and from GABRIEL and PIERSON [Eq. (25)], (13) can be represented as

$$\overline{R}^{O'}{}_m = m\bar{i}_1 = (m \cos \omega)\,\bar{i} + (m \sin \omega)\,\bar{j} \quad \ldots (14a)$$

$$\overline{R}^{O'}{}_{md} = \cos \beta\,[(m \cos \omega)\,\bar{j} - (m \sin \omega)\,i]$$
$$+ (m \sin \beta)\,\bar{k} \quad \ldots\ldots\ldots\ldots\ldots\ldots (14b)$$

or, from (14)

$$\overline{R}^{O'}{}_m = (m \cos \omega)\,\bar{i} + (m \sin \omega)\,\bar{j} \quad \ldots\ldots (15a)$$

$$\overline{R}^{O'}{}_{md} = -\,(m \sin \omega \cos \beta)\,\bar{i}$$
$$+ (m \cos \omega \cos \beta)\,\bar{j} + (m \sin \beta)\,\bar{k} \quad \ldots (15b)$$

Application of vector analysis for the solution of problems--Problem [after NEVIN, 1949, pr. 30, p. 378]: An inclined shaft is driven a length of 400 ft from a point A, with a bearing of 35W and a slope of 45°. At point B, which is at the same elevation as point A, but 500 ft west and 260 ft north of A, a hole is to be drilled as to intersect the lower end of the inclined shaft. Determine the bearing, slope, and true length of the drill hole.

Solution, first method: Assume the point A is the center of $\bar{i}, \bar{j}, \bar{k}$ coordinate system (see Fig. 3), where $\bar{i}$ axis (line ON_m) is oriented along the true north line, $\bar{j}$ axis along the east-west line, and $\bar{k}$ axis (line $A_1Z^1{}_m$) is a vertical line. The point B is located at the same level as the point A, with the length of AB equal to $\sqrt{500^2 + 260^2}$, or 563.6 ft. Draw a hemisphere of radius m equal to 563.6 ft and assume that the drill hole meets the inclined shaft at point F, whose plan view projection is point F_1. Designate

$$\text{Line } AB = \overline{AB} = \overline{R} \qquad (16a)$$

$$\text{Line } AF = \overline{AF} = \overline{T} \qquad (16b)$$

$$\text{Line } BF = \overline{BF} = \overline{X} \qquad (16c)$$

From (16) and Figure 3

$$\overline{R} = x_r\overline{i} + y_r\overline{j} + z_r\overline{k} \qquad (17a)$$

$$\overline{T} = x_t\overline{i} + y_t\overline{j} + z_t\overline{k} \qquad (17b)$$

$$\overline{X} = x_x\overline{i} + y_x\overline{j} + z_x\overline{k} \qquad (17c)$$

where $x_r, y_r \ldots x_t \ldots y_x, z_x$ are the corresponding coordinates of the vectors $\overline{R}, \overline{T}, \overline{X}$.

From the triangle $A_1F'_1F'_2$ (front view of Fig. 3)

$$A_1F'_2 = \text{length of the shaft} = 400 \text{ ft} \qquad (18a)$$

$$A_1F'_1 = A_1F'_2 \cos 45^\circ = AF^\circ_1 = 400 \cos 45^\circ \qquad (18b)$$

$$F'_2F'_1 = A_1F'_2 \sin 45^\circ = 400 \sin 45^\circ \qquad (18c)$$

From the triangle F_1F_oA (plan view of Fig. 3) and (18)

$$AF_o = AF_1 \cos 35^\circ = 400 \cos 45^\circ \cos 35^\circ = x_t \qquad (19a)$$

$$F_1F_o = AF_1 \sin 35^\circ = 400 \cos 45^\circ \sin 35^\circ = y_t \qquad (19b)$$

where $AF_1 = AF^\circ_1$.

From triangle ABC

$$x_r = 250 \text{ ft} \qquad (20a)$$

$$y_r = -500 \text{ ft} \qquad (20b)$$

$$z_r = 0 \qquad (20c)$$

By substituting the magnitudes of corresponding coordinates from (19) and (20) into (17)

$$\overline{R} = 260\,\overline{i} - 500\,\overline{j} \qquad (21a)$$

$$\overline{T} = (400 \cos 45^\circ \cos 35^\circ)\,\overline{i} - (400 \cos 45^\circ \sin 35^\circ)\,\overline{j} + 400 \sin 35^\circ\,\overline{k} \qquad (21b)$$

$$\overline{X} = x_x\overline{i} + y_x\overline{j} + z_x\overline{k} \qquad (21c)$$

However, from a closed vectorial triangle ABF we have

$$\overline{X} = \overline{T} - \overline{R} \qquad (22)$$

By substituting into (22) the vectorial expressions from (21) and by the law of association

$$x_x\overline{i} + y_x\overline{j} + z_x\overline{k} = (400 \cos 45^\circ \cos 35^\circ - 260)\,\overline{i} + (500 - 400 \cos 45^\circ \cos 35^\circ)\,\overline{j} + (400 \sin 45^\circ)\,\overline{k} \qquad (23)$$

From (23)

$$x_x = (400 \cos 45^\circ \cos 35^\circ - 260) = 231.7 - 260 = -28.3 \text{ ft} \qquad (24a)$$

$$y_x = (500 - 400 \cos 45^\circ \sin 35^\circ) = 500 - 162.4 = 337.6 \text{ ft} \qquad (24b)$$

$$z_x = 400 \sin 45^\circ = 282.8 \text{ ft} \qquad (24c)$$

From (24) the true length of the drill hole is

$$\sqrt{x_x^2 + y_x^2 + z_x^2} = BF = 441.2 \text{ ft} \ldots\ldots\ldots (25)$$

To determine the slope of the drill hole we have

$$\sin \beta = z_x/BF = 282.8/441.2 = 0.64098 \ldots\ldots\ldots (26)$$

or $\beta = 39° \, 52'$, approximately.

To determine the bearing of the drill hole

$$\tan \Omega = x_x/y_x = -28.3/337.6 = -0.08353 \ldots\ldots\ldots (27)$$

or

$$\Omega = -4° \, 46' \ldots\ldots\ldots (28)$$

or

$$90° - 4° \, 46' = 85° \, 14' \ldots\ldots\ldots (29)$$

Therefore, the bearing of the drill hole is S85° 14′ E.

Solution, second method: Assume $\bar{i}, \bar{j}, \bar{k}$; $\bar{i}_1, \bar{j}_1, \bar{k}_1$; and $\bar{i}_2, \bar{j}_2, \bar{k}_2$ systems with the same origin at point A (see Fig. 3). Draw two hemispheres whose radii are equal to m_1 units and m_2 units, respectively, where

$$m_1 = 400 \text{ ft} \ldots\ldots\ldots (30a)$$

$$m_2 = \sqrt{(500)^2 + (260)^2} = 563.6 \text{ ft} \ldots\ldots\ldots (30b)$$

Designate, as in the first method

$$\overline{AB} = \bar{R} \ldots\ldots\ldots (31a)$$

$$\overline{AF} = \bar{T} \ldots\ldots\ldots (31b)$$

$$\overline{BF} = \bar{X} \ldots\ldots\ldots (31c)$$

From (14) and Figure 3

$$\bar{R} = (m_2 \cos \beta_2 \sin \omega_2)\, \bar{i} - (m_2 \cos \beta_2 \cos \omega_2)\, \bar{j} \ldots\ldots\ldots (32a)$$

$$\bar{T} = (m_1 \cos \beta_1 \cos \omega_1)\, \bar{i} - (m_2 \cos \beta_1 \sin \omega_1)\, j + m_2 \sin \beta_1 \bar{k} \ldots\ldots\ldots (32b)$$

where $\beta_1 = 45°$; $\beta_2 = 0°$; $\omega_1 = 35°$; $\omega_2 = \tan^{-1} 260/500 = 27° \, 28.5'$.

By substituting the magnitudes of $m_1, m_2, \beta_1, \beta_2, \omega_1, \omega_2$, into (32)

$$\bar{R} = (563.6 \sin 27° \, 28.5')\, \bar{i} - (563.6 \cos 27° \, 28.5')\, \bar{j} \ldots\ldots\ldots (33a)$$

$$\bar{T} = (400 \cos 45° \cos 35°)\, \bar{i} - (400 \cos 45° \sin 35°)\, \bar{j} + (400 \sin 45°)\, \bar{k} \ldots\ldots\ldots (33b)$$

and from (33)

$$\bar{R} = (563.6_x \, 0.46134)\, \bar{i} - (563.6_x \, 0.88722)\, \bar{j} = 260\bar{i} - 500\bar{j} \ldots\ldots\ldots (34)$$

However, from the vectorial triangle ABF we have

$$\bar{X} = \bar{T} - \bar{R} \ldots\ldots\ldots (35)$$

By substituting into (35) the vectorial expressions from (33) and (34) and by equating the corresponding coordinates of the vectorial equation we obtain an equation identical to that of (24).

Summary and conclusions--A J. Willard Gibbs' vector system is established in a hemisphere of radius equal to m units and certain relationships are derived between the vector lines drawn in the same plane. It is probable that for certain types of problems related to mining geology two independent vectorial systems referred to the hemispheres of different radii should be used.

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AN ABUNDANCE MODEL FOR LEAD ISOTOPES BASED UPON THE CONTINUOUS CREATION OF THE EARTH'S SIALIC CRUST

Paul E. Damon

Abstract--A mathematical model for common lead isotope ratios is derived and evaluated. This model is based on a hypothesis by J. Tuzo Wilson concerning the origin of the continents. It can be shown that Holmes' equation of the isochron becomes a special case of a more general equation. The age of the Earth's sialic crust for Holmes' hypothesis corresponds to the age of the ancient nuclei of the continents for the continuous creation hypothesis. It may be necessary to assume that a lead deposit can be derived from either sial or sima, or both sial and sima to account completely for known variations in common lead isotope ratios. An attempt should be made to correlate common lead isotope ratios on a regional basis. These ratios are apparently not, in themselves, quantitative criteria for age of deposition.

Introduction--Although there are several hypotheses for the origin of the continents [GUTENBERG, 1951], the determination of the age of the Earth's crust has been based on HOLMES' method for analysis of common lead isotope ratios which tacitly assumes a rapid initial segregation of the Earth's crust into sial and sima. WILSON [1949, 1952ab] following certain ideas of LAWSON [1932] has advanced the hypothesis (in contrast to Holmes' assumptions) that the continents have been in the process of growth throughout geologic time by segregation from an originally uniform, simatic crust. According to this point of view, the greenstone volcanic provinces are the original ancient nuclei of the continents, and these have grown in situ by the reworking of andesitic volcanic material. In addition to arguments concerning the physical and geological plausibility of Wilson's hypothesis, there are a considerable number of age determinations which tend to support the hypothesis [FARQUHAR, RUSSELL, and WILSON, 1953].

In a previous paper concerning common lead isotope ratios the author [DAMON, 1953] has pointed out that, although there are significant non-random deviations from theoretical expectation based on Holmes' hypothesis, the data taken together appear to be in general agreement with the assumptions made. However, certain deductions (for example, the origin of the lead) depend upon the assumptions made, and the exact meaning of the "age of the Earth's crust" computed from lead isotope ratios by Holmes' method becomes obscure. For these reasons it becomes of interest to investigate a mathematical model based on the continuous creation of the Earth's sialic crust.

An alternative mathematical model--A simple, mathematical model can be derived, based upon Wilson's hypothesis, which serves to explain the observed abundances of common lead isotopes. The lead, in this case, must be considered to have passed through three phases: (1) The simatic phase in which the uranium, actinouranium, and thorium abundances relative to Pb^{204} at any time t are U_t^b, V_t^b, W_t^b respectively; (2) the sialic phase in which the uranium, actinouranium, and thorium abundances at any time t are U_t^a, V_t^a, W_t^a respectively; (3) the mineral deposit phase in which the lead is separated from contact with the parent elements and any further contamination by radiogenic lead will be considered anomalous.

Time and abundance symbols will be redefined as shown in Figure 1.

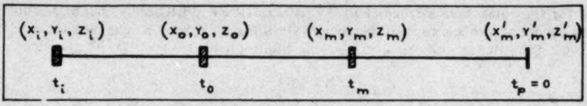

Fig. 1--Key to time and abundance symbols

The time of the first segregation of sialic material from the basaltic protocrust is t_i. It may be considered as the birth date of the infant continents.

The time of segregation from the basaltic crust of the particular sialic material from which the particular lead deposit under consideration will be formed is t_o. It is the time of transition from phase 1 to phase 2.

The time of formation of the lead deposit is t_m.

(X_i, Y_i, Z_i) . . . are the isotopic abundances of Pb^{206}, Pb^{207}, and Pb^{208}. The times are indicated by the subscripts.

$X_m = X'_m$ unless anomalous radiogenic contamination has occurred.

It can readily be seen that

$$X_m = X_i + (X_o - X_i) + (X_m - X_o) \qquad (1)$$

or

$$X_m = X_i + \gamma\, U_p^a\,(e^{\lambda_1 t_i} - e^{\lambda_1 t_o}) + U_p^a\,(e^{\lambda_1 t_o} - e^{\lambda_1 t_m}) \qquad (2)$$

where U_p^a is the uranium abundance at the present time in the acidic phase and γ is the ratio of the abundance of uranium in the simatic and sialic phase - $\gamma = U_p^b/U_p^a$.

Similar equations can be written for the abundance of Pb^{207} and Pb^{208}.

Let us consider the abundances for the two limiting cases: (a) $t_i = t_o$, that is, the case where the lead deposit is formed from the oldest part of the sialic crust; (b) $t_o = t_m$, that is, the case where the lead deposit is formed directly from the simatic material at the time of segregation.

$$\text{Case (a)} \quad X_m = X_i + U_p^a\,(e^{\lambda_1 t_i} - e^{\lambda_1 t_m}) \qquad (3)$$

$$\text{Case (b)} \quad X_m = X_i + \gamma\, U_p^a\,(e^{\lambda_1 t_i} - e^{\lambda_1 t_m}) \qquad (4)$$

All Pb^{206} abundances should fall within the curves defined by cases (a) and (b) in the absence of appreciable complicating factors.

The equation of the isochron is

$$1/r = \frac{(X_m - X_i)}{(Y_m - Y_i)} = \frac{\gamma\, U_p^a\,(e^{\lambda_1 t_i} - e^{\lambda_1 t_o}) + U_p^a\,(e^{\lambda_1 t_o} - e^{\lambda_1 t_m})}{\gamma\, V_p^a\,(e^{\lambda_2 t_i} - e^{\lambda_2 t_o}) + V_p^a\,(e^{\lambda_2 t_o} - e^{\lambda_2 t_m})} \qquad (5)$$

for case (a) and also for case (b)

$$1/r = U_p^a/V_p^a\, \frac{(e^{\lambda_1 t_i} - e^{\lambda_1 t_m})}{(e^{\lambda_2 t_i} - e^{\lambda_2 t_m})} \qquad (6)$$

A solution of the general equation (5) should give approximately the same values as obtained previously by Holmes' method, $t_i = 3.5 \times 10^9$ years, $X_i = 11.3$, $Y_i = 13.5$ [COLLINS, FARQUHAR, and RUSSELL, 1953].

Evaluation of the model--U_p^a and $\gamma\, U_p^a$ can be evaluated from Table 1 and the accepted value (1.48 pct) for the relative abundance of Pb^{204} [HOLLANDER, PERLMAN, and SEABORG, 1953]. The decay constants are known, and the above values for t_i, X_i, and Y_i can be used as a first approximation. Substituting numerical values, the limiting equations for Pb^{206} are

$$\text{Case (a)} \quad X_m = 11.3 + 13.6\,(1.71 - e^{1.54\times 10^{-10} t_m}) \qquad (7)$$

$$\text{Case (b)} \quad X_m = 11.3 + 6.3\,(1.71 - e^{1.54\times 10^{-10} t_m}) \qquad (8)$$

These equations for Pb^{206} and also equations for Pb^{207} are plotted in Figure 2. With a few exceptions, the data by NIER [1938, 1941], COLLINS and Others [1953], and VINOGRADOV and

Table 1--Measured uranium-thorium-lead abundance

Rock type	Uranium	Thorium	Th/U ratio	Lead
	gr/ton	gr/ton		gr/ton
Acid igneous	3.0 ± 0.3[a]	13 ± 2[a]	4.4	19[c]
Intermediate igneous	1.4 ± 0.2[a]	4.4 ± 1.2[a]	3.1	..
Basic igneous	0.96 ± 0.1[a]	3.9 ± 0.6[a]	4.1	9[c]
Sedimentary	1.2 ± 0.1[a]	3.3 ± 0.7[a]	2.7	..
Granitic	3.82[b]	12.48[b]	3.27	16[c]

[a] EVANS and GOODMAN [1941].
[b] SENFTLE and KEEVIL [1947].
[c] SANDEL and GOLDICH [1943].

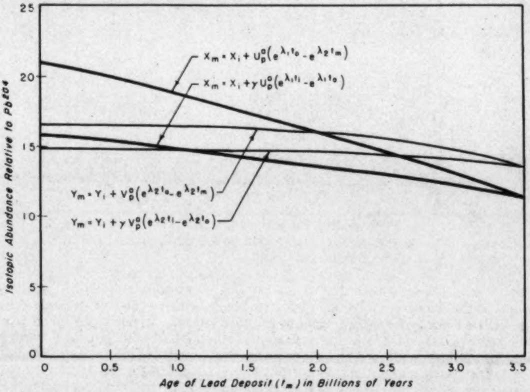

Fig. 2--Limiting equations for the relative abundances of Pb^{206} and Pb^{207} based on the hypothesis of the continuous creation of sialic material

Others [1952] for which geologic ages are given fall within the limiting equations. The maximum deviation is observed for the Joplin, Missouri, ore (7 pct high Pb^{206}), but this is still well within the limiting equations if the uncertainty in the value of U_p^a is taken in consideration.

In evaluation of the isochron ratio r, the upper limit (Fig. 3) is provided by (6) which is identical with the equation used in Holmes' method. This upper limit is independent of the value of U_p^a or γU_p^a. To evaluate the lower limit, (5) must be solved for the minimum value of r at various times of deposition t_m. This lower limit is dependent on the values assumed for U_p^a and and γU_p^a. The computed values of r for about 75 pct of the lead deposits, previously referred to, fall within the limiting curves. Most of the remaining values fall above the upper limit. The use of the values of t_1, X_1, and Y_1 from the approximate solution and the sensitivity of the ratio r to small errors in the determination of Pb^{206} and Pb^{207} may account in part for the discrepancy. An error of one per cent in the determination of these values can cause a ten per cent error in the computed value of r.

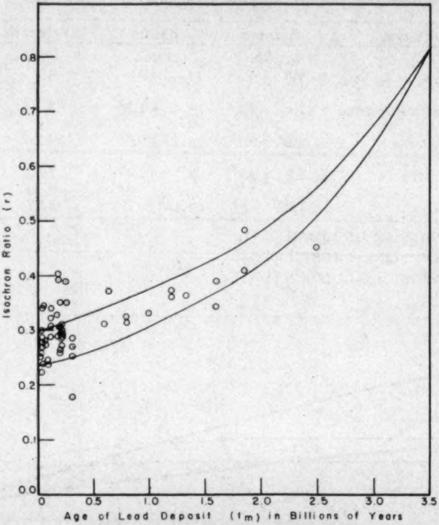

Fig. 3--Limiting equations for the isochron ratio based on the hypothesis of the continuous creation of sialic material

Discussion--It has been shown that cases (a) and (b) reduce to Holmes' equation of the isochron. The age of the Earth's sialic crust for Holmes' model t_0 is very nearly the same as t_1, the age of the ancient nuclei of the continents for this model. It can be deduced from Holmes' model that the lead is derived from sialic material [DAMON, 1953], but this deduction is dependent upon the assumptions made and the model cannot account for the large deviations from expectation without invoking anomalous conditions (that is, failure of the assumptions). The model based on continuous creation of sialic material assumes that the lead can be derived from either sial or sima at a variable time t_0. These assumptions account for most or all of the deviation from expectation for Pb^{206} and Pb^{207} but do not account for all of the deviation from expectation observed for the isochron ratio r.

If the discrepancy noted is real and not due to error in measurement, then it is possible to derive another model embodying a geologic hypothesis which will account for the high values of the isochron ratio as follows:

(1) At time t_1 the parent material of both sima and sial is formed as a distinct geologic entity.

(2) At time t_0 both sial and sima are segregated from the parent material.

(3) At time t_m a lead deposit is formed from either sima or sial or both sima and sial.

A necessary but not sufficient condition for the validity of a geologic hypothesis, concerning early earth history and the orogenetic process, is that it must account for the variation in common lead isotope ratios. It is possible that more than one hypothesis may be satisfactory in this respect but may fail to conform to other geologic conditions.

Because t_0 may be considered to be a constant for genetically similar geologic regions, it would seem that an attempt should be made to correlate lead isotope ratios on a regional basis. It would seem from data now available that lead isotope ratios are not, in themselves, quantitative criteria for age of deposition.

The author believes that the study of common lead isotope ratios will eventually lead to fundamental information concerning the early history of the Earth and present and past geologic processes.

This work was supported in part by the U. S. Atomic Energy Commission. The author is indebted to J. Tuzo Wilson and his co-workers of the Geophysical Laboratory of the University of Toronto for conversations and correspondence which led to the formulation and investigation of this lead-isotope model.

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GEODETIC OPERATIONS IN MEXICO FROM JUNE, 1952, TO MAY, 1953

Manuel Medina

(Translated by Maria T. Perri)

Triangulation--With some interruptions due to bad atmospheric conditions angular observations continued on the projected arc of triangulation in the State of Chiapas, which will shortly complete the triangulation tie with the triangulation of Guatemala.

The observations on the chain along the 23rd parallel have been temporarily suspended in order to assign all the available elements to the Chiapas arc.

Bases--Computations were completed for the Cedros base, measured in the State of Zacatecas, with the following results:

Length of the base reduced to sea level	9002.486157 m
Probable error	± 0.007575 m
Relative error	1:1,188,270
Length of the base through triangulation	9002.443000 m
Relative error of the triangulation	1:208,000

Astronomic geodesy--The Laplace stations recently completed and which were mentioned in the previous report are: Monte Albán, on the 98° meridian arc; Primales, on the 101° meridian arc; North end of the Tehuantepec Base (Oaxaca-Chiapas arc); and North end of the Bermejillo Base, 103° meridian arc.

The respective computations were completed, obtaining results within the acceptable tolerances.

Precise leveling--Precise level observations continued in the Tehuantepec Isthmus and in addition the Military Cartographic Commission of the Secretary of National Defense undertook various precise levels on both coasts with the object of obtaining an elevation connection of the tide gages installed on the coasts.

Gravity--The Geophysical Institute with the cooperation of various national and foreign institutions was entrusted with the development of gravimetric operations in Mexico for the past two years. Gravimetric determinations were made with a Worden gravimeter, transported by plane between the northern and southern frontiers of the country, making observations at each of the intermediate airfields, and also making determinations on the highways, with automobile transportation, at approximately ten-kilometer intervals.

With pendulum equipment from Columbia University, U. S. A., and from Cambridge University, England, on two distinct expeditions, g values were determined at the fundamental base in Tacubaya and at the Polytechnic Institute of Monterrey.

Cartography--A new map of the State of Guerrero was edited at a scale of 1:500,000 with 200-meter contour intervals.

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(Manuscript received March 23, 1953; presented at the Thirty-Fourth Annual Meeting, Washington, D. C., May 4, 1953; open for formal discussion until January 1, 1955.)

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REPORT OF THE COMMITTEE ON CLOUD PHYSICS, 1951-1953

H. Weickmann, Chairman
Charles E. Anderson   Ferguson Hall
George S. Benton   Roscoe R. Braham   Christian Junge

(The extensive list of References for this report is being published in the July 1954 issue of Meteorological Abstracts and Bibliography, Part III, where it is believed it will serve the widest possible use, inasmuch as it is quite a complete bibliography of published material on Cloud Physics issued during the period covered by this report. The list is divided into eight groupings, labeled A to H, each alphabetical by authors. The headings of the groupings B to H correspond to the section headings of this report, bearing the same letter as that appearing in the section heading. The letter A applies to a general group entitled Books and Reviews in the published list.

The references shown are for the most part listed under the same heading in both the report and the published list, but there are some exceptions, most notably perhaps with respect to List A, but there are other exceptions as well, for example [REYNOLDS, 1953] cited in Section C is found in List G, where, as a thunderstorm paper, it belongs. Usually, as in this case, the context will guide one to the proper list. The list also contains items not specifically referred to in the report. - Ed.)

B. Papers on nuclei--Though the scale of aerosols reaches over several orders of magnitude [JUNGE, 1952a], it is probable that only the larger particles act primarily as condensation nuclei, but they may originate from coagulation of smaller ones [JUNGE, 1952]. The electron microscope is the tool most frequently used for these studies [FACY, 1951ab, 1952; KUROIWA, 1951, 1953; KUMAI, 1951; DESSENS, LAFARGUE, and STAHL, 1952; OGIWARA and OKITA, 1952; AUFM KAMPE, WEICKMANN, and KEDESDI, 1952; JACOBI, JUNGE, and LIPPERT, 1952]. The French believe that sea salt is the main constituent, whereas the Japanese state that sea spray appears to be an insignificant source, a fact already pointed out in 1941 by G. C. Simpson. Salt particles may nevertheless play a role in precipitation processes. WOODCOCK [1951, 1952ab] measured number and size (mass) of salt particles as a function of height over Woods Hole and Florida and of both height and wind force over Hawaii.

For the generation of salt nuclei from the ocean surface, two mechanisms seem to be responsible: (1) the generally known "sea-spray mechanism," and (2) the "bubble-break mechanism" in foaming sea water. BOYCE [1951], FACY [1951b], and WOODCOCK [1952b] independently called attention to the second. Stuhlman [BOYCE, 1951; WOODCOCK, 1952b] first observed that small air bubbles bursting in distilled water ejected a great number of tiny droplets into the air (up to 14 cm above the water surface). The same effect occurs in sea water and is basically different from the sea-spray mechanism. Bubbles form and break during calm sea, for instance in the surf, but sea spray is only connected with a heavy wind. Measurements of airborne salt particles [CROZIER, SEELY, and WHEELER, 1952] showed that the greatest abundance of chloride particles was in air that probably came from a tropical storm.

JUNGE [1952b] concluded that particles of natural condensation nuclei are mixed from solid and liquid substances, with gas adsorption often altering the original composition. JUNGE [1953], with Jacobi and Lippert, undertook analysis by electron diffraction patterns, apparently a better method than electron microscope, which showed agreement with the diffraction pattern of ammonium sulphate. Microchemical analysis of the aerosol agreed. KUROIWA [1953] reported fogs and clouds in Hokkaido formed on nuclei 50 pct of which are combustion products, 20 pct soil materials, and 20 pct sea salt, while the remainder formed without visible nuclei.

Contributions have been made on nuclei counts over the oceans [HESS, 1951; OHTA, 1951; MOORE, 1952; PARKINSON, 1952] and shape, constitution, and concentration of meteoritic dust [THOMSEN, 1953]. Accuracy of the Aitken nucleus counter has been checked in the light of increased knowledge about constitution and properties of the aerosol [JUNGE, 1952; HOSLER, BURKHART, and NEUBERGER, 1952]. SCHAEFER [1953] found that the number of ice nuclei on Mt. Washington increased considerably during 1949-1953.

C. Papers on formation and properties of cloud particles--MASON [1951] explains certain condensation phenomena on the basis of Volmer's theory of phase transition and on Volmer and Flood's experiments, whereas FARLEY [1952] questions these same experiments. FARLEY's [1951] investigation of the effect of ultraviolet light upon condensation in an expansion chamber confirm essentially the extensive work of LENARD and RAMSAUER [1911, 1912]. These investigations are of possible importance in explaining mother-of-pearl clouds.

Theoretically, two processes of nucleation for ice formation exist. In the heterogeneous one a nucleus acts as catalyst between vapor and ice or water and ice, whereas in the homogeneous one no nucleus is present, and ice formation takes place because the vapor or water phase becomes thermodynamically unstable.

WEICKMANN [1951] explained ice formation by means of oriented overgrowth (epitaxy) of water over a crystalline freezing nucleus whose surface is structurally similar to an ice plane. This theory explains observed thresholds of ice formation near -20, -30, -40, and -60°C. MASON [1952] based a theory of the -40°C-threshold upon Volmer's, Becker-Doering's, and Turnbull's thermodynamic theories on phase transition and considered it as a basic threshold if evaluated with a value of 22 erg/cm^2 for the unknown interface energy between water and ice. McDONALD [1952] cited errors in Mason's calculations and suggested 16 erg/cm^2 as more realistic for the interface energy, though with this value the fundamental transition temperature would theoretically rise to -26°C. POUND, MADONNA, and PEAK [1952] gave experimental evidence for -40 ± 2°C.

RAU [1951] found that electrical sparks, and even electrical potentials, seem able to produce ice crystals in super-cooled water near freezing and thus gives a more realistic background to the dipole theory of HOSLER [1951]. Considerable physico-chemical literature exists on this subject [HAMMER, 1938; SWINNE, 1936]. The electrical field itself has no nucleating property but favors nucleation of dipole liquids on the nuclei present.

Mason's and McDonald's calculations have shown clearly that ice crystal formation is extremely sensitive to the value of the interfacial energy between ice and water and that a small change in this value may alter the freezing temperature considerably. Orientations of the water molecules of an adsorbed or condensed water film implied either by the structure of the nucleus [WEICKMANN, 1951] or its electrical charge [RAU, 1951; HOSLER, 1951] may consequently diminish this energy (the water becomes more ice-like) and start crystallization. Salt nuclei are also considered in the field of ice nucleation by BIRSTEIN and ANDERSON [1953]. AUFM KAMPE and WEICKMANN [1951] found the number of freezing nuclei in natural aerosol increases almost linearly on a logarithmic scale from about one per liter between -10 and -15°C to about 10,000 per liter between -24 and -35°C. Non-hygroscopic AgI was found superior to hygroscopic cadmium iodide and cobalt iodide.

REYNOLDS, HUME, VONNEGUT, and SCHAEFER [1951] found that bright sunlight decreases the efficiency of AgI considerably as did INN [1951] who explained the decrease by photolysis. VONNEGUT and NEUBAUER [1951] observed that AgI is not completely destroyed but regains its efficiency, at least in part, during the night. REYNOLDS, HUME, and McWHIRTER [1952] showed deactivated silver iodide can be reactivated. BIRSTEIN [1952] found that silver iodide can be protected from deterioration by a thin film of water.

BREWER and PALMER [1951] confirmed Cwilong's previous findings that only water contaminated by alcohol exhibits the characteristics of super-cooling and crystallization found by Rau. BIGG [1953] concluded that simple probability can explain an approximately linear relationship found between the diameter (on logarithmic scale) and the mean freezing temperature. RAU [1953] concluded that different freezing temperatures are due to a "statistical volume effect." WYLE [1953] studied freezing of super-cooled water in glass capillaries. DORSCH and BOYD [1951] investigated important physical properties of water (x-ray diffraction study of the internal structure of super-cooled water); and HACKER [1951], experimental values of the surface tension of super-cooled water.

HITSCHFELD [1951], KINZER and GUNN [1951], and BEST [1952] dealt experimentally and theoretically with the growth of cloud droplets and formation of droplet spectra. SQUIRES [1952] and BEST [1951] confirmed Howell's finding that the spectrum of condensation nuclei has little influence on the formation of droplet spectra and that processes in the cloud base (rate of updraft and concentration of nuclei) are more significant. (This is true in spite of an error in the application of Raoult's law in Howell's calculations [McDONALD, 1953].) GUNN and HITSCHFELD [1951] concluded from experiments that (1) Langmuir's theory of collection efficiency is valid, and (2) there is no difference between collision efficiency and collection efficiency, that is, every drop-droplet collision results in coalescence. SCHUMANN's [1940] "mechanical" and VIERHOUT's

[1949, 1950] "thermodynamical" theories on coalescence (the latter also under consideration of the coexistence of ice crystals and droplets) need confirmation, the more since ZAYTSEV's [1950] and WEICKMANN and AUFM KAMPE's [1953] observations of the microphysical structure of cumulus-type clouds suggest an active mechanism of coalescence among cloud droplets. The processes of "bounce-off" (droplet from droplet, droplet from ice particle), "blow-off" or splashing (essentially water from ice), and "splinter" formation (ice from ice) are as unexplored as coalescence and yet some are already integral parts of theoretical considerations, for instance, formation of splinters as ice nucleation source [CENTENARY PROC. R. MET. SOC., 1950] or blow-off as charge-separating mechanism in thunderstorms [REYNOLDS, 1953].

Laboratory and natural observations of ice crystal forms have been made by AUFM KAMPE, WEICKMANN, and KELLY [1951], Nakaya [MALONE, 1951], GOLD and POWER [1952], MASON and OWSTON [1952], ITOO [1951ab, 1953ab], SOULAGE [1953], and YAMAMOTO and Others [1952]. WEICKMANN [1950] attempted to explain qualitatively the occurrence of different crystal forms from internal and external factors; MASON [1953] tried to find analytical expressions for the conditions of lamellar or prismatic growth. The basic laws governing growth of crystals are not too well understood as yet. Following Houghton, AUFM KAMPE [1952] applied the theory of the growth of water droplets from vapor in order to determine the rate of growth of ice crystals from vapor and found that, in convective cirrus clouds, water saturation can be maintained in the presence of ice crystals, whereas in cirrostratus-type clouds, the humidity will be closer to ice saturation. MAGONO [1951, 1953] dealt with the fall velocity of snow flakes and growth of snow flakes and graupel. An experimental study on growth of ice crystals was made by REYNOLDS [1952], whereas MELCHER [1951] studied the riming process. JONA and SCHERRER [1952] described a method of growing, from slightly super-cooled water, large single ice crystals suitable for laboratory investigations. HUMBEL, JONA, and SCHERRER [1953] have measured the dielectric constant of ice using such crystals.

D. Papers on formation and properties of clouds--Three models of cumulus convection were presented: (1) Where the whole cloud mass is affected by entrainment of outside air, treated theoretically by STOMMEL [1951] and HOUGHTON and CRAMER [1951]. The latter authors in one case calculated the height of cloud base, vertical velocity, and liquid water content in the cloud for air assumed to rise from the ground. The calculated height checks well with the base of cumulus determined experimentally [MOLTCHANOFF, 1924]. The updraft velocity in the cloud base agrees with measurements of PIELSTICKER [1940] using a sailplane, and the liquid water content is in agreement with measurements of WEICKMANN and AUFM KAMPE [1953]. A case of a cloud rising into very dry environment indicated that the cloud cannot be "dried out." Unfortunately, the mathematical expression is only numerically evaluable. STOMMEL [1951] derived a simpler formula to calculate updraft velocity without consideration of the weight of the liquid water and for steady state conditions and applied it for trade-wind cumuli or fair-weather cumulus up to cumulus congestus. (2) For cumulus congestus and cumulonimbus, SCORER and LUDLAM [1953] postulated that convection is characterized by a "bubble" mechanism, updraft within the cloud being the integral of many big bubbles, each has its own entrainment mechanism, and its wake prepares the path for the next bubble. The model is discussed in the Quarterly Journal of the Royal Meteorological Society, v. 79, 1953, and questioned by MALKUS [1952ab, 1953] who has made contributions to cumulus dynamics. (3) A third, taking shape in papers by BRAHAM [1952], BYERS [1952], and WEICKMANN and AUFM KAMPE [1953] can be called the "chimney" or "vertical jet" model and is typical essentially for heavily precipitating cumulonimbus clouds. Here strong and persistent up-and-down drafts are confined to columns narrow by comparison with the over-all dimensions of the cloud. An aircraft [BYERS, 1952] detected a width of about 1.5 miles for such an updraft. The temperature within the updraft was about 5°C warmer than the environment. The average width of an updraft column is given as about one mile [BRAHAM, 1952]. In the center of these columns entrainment is of secondary significance and the lapse rate is nearly moist-adiabatic, making the water content higher than under consideration of entrainment. Thus, Weickmann and Aufm Kampe found values of liquid water content up to ten gr/m^3.

LANGWELL [1951] found that a cellular convection exists within the trade cumulus layer over the Caribbean Sea, initiated not by a heat source below but by a cold source above. LANGWELL [1953] saw the primary cause in "oscillations of the boundary between the well-mixed layer near the ocean and the cloud layer." Regarding Bénard cells see JONES [1952] and FOSTER [1952].

FARQUARSON [1952] drew attention to the fact that the frost point at the tropopause was more than 20°F lower than at the altitude of a stratospheric cloud. Apparently, "the high cloud was the precursor of a vigorous depression . . ." AUFM KAMPE [1952] discussed theoretically the humidity conditions in cirrus and cirrostratus. Weickmann and Aufm Kampe found droplet radii up to

100 microns in cumulus congestus and in cumulonimbus even if the clouds did not reach the freezing level. The trend of droplet number versus height above base suggests that coalescence is at work. AUFM KAMPE and WEICKMANN [1952] discussed calculation of a cloud's liquid water content with known visibility and droplet spectrum and showed that the "constant" in Trabert's formula is really a variable.

E. Papers on natural precipitation--Theoretical discussions of natural formation of precipitation particles [HOUGHTON, 1950; BOWEN, 1950; LUDLAM, 1951a] have established that Langmuir's drop collision theory describes a mechanism equally important as Bergeron-Findeisen's ice crystal theory for the explanation of precipitation.

A theoretical treatment of the microphysical processes of shower formation [LUDLAM, 1951ab, 1952ab] showed complexity for clouds with and without ice crystals. The occurrence of giant cloud droplets in cumulonimbus would reduce the theoretical difficulty since they are already big enough to start an efficient process of coalescence below the freezing level as well as after crystallization above the freezing level. Woodcock's research on giant salt nuclei is incorporated in LUDLAM's [1951b] theory of the mechanism of drizzle showers over the ocean. MASON [1952] demonstrated in a theoretical study the difficulty of obtaining droplets large enough for coalescence without starting out from nature-furnished "trigger particles," and assumed, therefore, that the lifetime of some droplets normally determined by eddy diffusion from the cloud interior to the boundaries is considerably increased over that of the bulk. In stratus, three to four hours would be required to produce by condensation a droplet large enough for coalescence.

A theoretical analysis [WEICKMANN, 1952] is based upon BERGERON's [1950] model of a releaser cloud, the altostratus, where ice crystals grow due to sublimation, and of a spender cloud, the nimbostratus, where coalescence above and below the freezing level is the predominant growth process.

Observations on formation of rain from non-freezing clouds were reported by SMITH [1951], WARD [1952], BATTAN [1953], and STYLES and CAMPBELL [1953] who investigated forming rain below the freezing level using airborne radar. The last authors derived curves for growth and concentration of the rain drops.

F. Papers on artificial precipitation and cloud modification--HALL [1952a], DUFOUR [1952], and BYERS [1953] described the intense world-wide research related to weather control. Attention is called to the final reports of Project Cirrus by SCHAEFER [1953] and LANGMUIR [1953].

KRICK and SMITH [1951], evaluating sustained cloud-seeding operations over regions amounting to a maximum of nine million acres, avoided enlarging on the problem of how the seeding agent arrives at the right place at the right time, and whether or not it will act as it is supposed to, but concluded that significant increases in monthly rainfall totals could be achieved, and "that rainfall during seeding periods has been more evenly distributed and gentler than has been customary in past years." WEICKMANN [1952], however, found that precipitation intensity is primarily governed by the rate of updraft, that is, by the large-scale circulation, and that the number of precipitation particles is of secondary importance. In special cases intensity may be influenced, but then the structure of precipitation will not become more evenly distributed but will, on the contrary, acquire a more shower-like character.

HALL [1951] showed that a seven-day periodicity in weather which fitted best the operation schedule of the AgI-burner in New Mexico was dominant during April, 1950, from the middle Pacific through the United States and the Atlantic Ocean to Europe. HOLZMAN [1951] quoted from a Russian book on weather forecasting, a table containing weather periods during 1926-1935 showing that a period of seven days was the most frequent. Similar papers, contributed by LEWIS [1951] and WAHL [1951], demonstrated that a seven-day period in weather is common. Finally, HAWKINS [1952] found for May, 1952, a seven-day periodicity in Washington, D. C., rainfall record whose amplitude was even more pronounced than that noted at Washington during the New Mexico seedings in April and May, 1950.

SMITH [1952] defined a "rain-making index" composed of four factors which have proved to be of special significance in production of rain. Values for these factors, (1) synoptic situation, (2) water content 2000 ft above the freezing level, (3) height of the freezing level, and (4) lapse rate 10 and 0°C levels, are summed giving the rain-making index, which has a good correlation with chance of success.

A series of papers on modification of super-cooled stratus and stratocumulus appeared [DESSENS, SOULAGE, and ALBY, 1953]. The authors studied droplet distribution in clouds, crystal types after seeding with AgI, and halos that the crystals caused. Similar experiments were made by YAMAMOTO and Others [1952]. SHELLARD and GRANT [1951] (while airborne) took photographs as well as radar pictures (horizontal map and vertical cross-section) of seeding results.

LANGMUIR [1953] in his final report on Project Cirrus concluded: "The cumulated evidence presented in these chapters constitutes a proof of the seeding hypothesis, according to which localized, periodic seeding with only two pounds of silver iodide per week has produced profound periodic changes in weather at distances that extend many thousands of miles from the point of seeding." BYERS [1953], however, concluded ". . . there is still a vast amount of fundamental work and rigid testing to be done before a scientific evaluation of rain making can be accomplished."

The U. S. Weather Bureau at present is involved in such a rigid test of seeding in the States of Washington and Oregon [HALL, 1952b]. Another potential test area (the snow belt at the eastern end of Lake Ontario) is especially suitable for studies of showers [JOHNSON and MOOK, 1953].

As to atomic bombs and weather, HOLZMAN [1951] concluded "A very small-sized but moderate warm front rainstorm releases energy at the rate of at least three atomic bombs per second."

G. Papers on thunderstorms, hailstorms, tornadoes, and thunderstorm electricity--The thunderstorm as a thermodynamic engine was discussed by BRAHAM [1952], who defined the dimensions of an average thunderstorm cell and studied the water and energy budget. He found the following sources and sinks: water sources - total inflow of water vapor into thundercloud; water sinks - (1) precipitated water, (2) evaporation into downdraft, (3) evaporation from cloud edges; energy sources - (1) released latent heats of condensation and fusion, (2) force of gravity acting on the cold air of the downdraft; energy sinks - (1) increases in internal and potential energy of the environment, (2) energy expended in lifting water particles, (3) work done in separating electrical charges with discharge to the ground. Based upon results of the Thunderstorm Project, it was possible to attach numerical values to the different factors and to study the atmospheric conditions required for development of such a thunderstorm engine. FAUST [1951] showed how the "first gust" and the "pressure nose" could be explained by the action of out-flowing cold air formed below the freezing level due to melting of precipitation particles. (This explanation of thunderstorm downdrafts considers only one downdraft mechanism and agrees with MULL and RAO [1950]. One result of the Thunderstorm Project was, however, that downdrafts can also be generated by entrainment of outside air into the initial updraft above the freezing level.) A scheme of different stages in the development of a thundercloud considering the cold air source below the freezing level was presented. Probability of the occurrence of thunderstorms and a method of how to judge the "thunderstorm readiness" from available meteorological and aerological data were also given. A review of different downdraft mechanisms was published by CHONDHURI [1952]. SCHAEFER [1952] reconsidered his theory on the thunderstorm high and applied it to the deceleration of the downrushing cold air near the ground. The pressure rise at the ground due to upward steady-state acceleration would be no greater than 1/4 mb, whereas the pressure rise associated with non-steady deceleration near the ground would be around 1/2 mb.

In a theoretical analysis of the precipitation mechanism and the charge generation given by REYNOLDS [1953], the growth is based upon Langmuir's drop collision theory, whereas the Workman-Reynolds effect of charge generation and Ludlam's theory of the "wet hailstone" are the basis for the charge separation mechanism. For New Mexico thunderstorms, the negative charge center should be located in the region of the cloud characterized by temperatures between -1 to -10°C. BERRY [1952] reported that only 45 minutes were required from the first cumulus humilis to the discharge of heavy rain and some hail from a full-fledged thunderstorm.

FETERIS [1952] reported that in a thunderstorm survey by a close network of observers, location of cloud to ground lightning flashes were plotted on a map to yield data on lifetime and direction of motion of such "lightning centers." One thunderstorm cell seems to be composed of several lightning centers, each having a very small diameter (several hundred yards).

With regard to hailstorms, FAWBUSH and MILLER [1953ab] suggested to forecast hailstone sizes on the assumption that big hailstones with a great fall velocity grow only in fast updrafts. WEICKMANN [1953], however, proposed that the persistence rather than the speed of the updraft leads to large hailstones.

Concerning tornadoes, a series of radar pictures by STOUT and HUFF [1953] show the development and rapid growth of the "tornado cyclone" [BROOKS, 1949]. Tornado studies for forecasting purposes are given by FAWBUSH and MILLER [1951, jointly with STARRETT; 1952ab].

On the subject of thunderstorm electricity, SCHONLAND and MALAN [1950; MALAN and SCHONLAND, 1951ab], in investigations of the intermediate field changes between the strokes of a multiple lightning flash, concluded that all strokes originate in one charged column inside the thundercloud. Such a column discharges vertical segments with an average of one stroke per kilometer. Usually none of the strokes originates at levels higher than nine km, intensity of the discharge decreasing with each stroke. Six km, average level of the third stroke, is most frequently the top of this column. The average temperature here was -19° C. The authors are convinced that the charge generating process is situated above the freezing level, probably between six and nine km, that is, between about -19 and -40° C. This is somewhat contradictory to an explanation by means of the Workman-Reynolds effect [REYNOLDS, 1953]. The authors believe that the positive space charge below the freezing level triggers-off in 65 pct of all cases the first discharge of the column, that it is situated in the level of the cloud base and that it is due to a concentration of "upward-moving positive ions produced by point discharge from the ground."

Radar investigations of the vertical structure of overhead thunderstorms carried out by Browne [WORMELL, 1951] revealed an extremely intensive echo from a region of limited vertical extent near the base of the cloud several thousand feet below the freezing level. In order to explain this echo, an intensive process of drop-breaking and regrowth is required. Strong, positive potential gradients simultaneously observed with these echoes seem to indicate that the breaking-drop mechanism as proposed by Simpson and Scrase is actively at work as charge generator for the lower positive space-charge pocket.

The average height of lightning strokes to ground was measured by BARNARD [1951] by means of a network of three stations. From the electrostatic field change at any one of these stations, the height can be calculated. The average height of ten flashes (including multiple strokes) turned out to be 5.2 km above ground. On the average, 17.8 coulombs were discharged per stroke.

Lightning research at Cambridge [GOLD, 1952] yielded the result that of 1500 recorded discharges, 37 pct reached the ground, 32 pct brought down negative charge, 3 pct positive charge only, and 2 pct both charges. Forty-five per cent of all flashes were within the cloud and took negative charge upwards.

MEINHOLD [1951], flying through cumulus with 300 km/hr at a temperature of -5.5° C, observed that icing resulted in a strong negative potential of the iced body. The intensity of the charge generation is estimated to be about 5×10^{-12} coul/cm^2 sec. An analogous observation in supercooled fog has been reported by LUEDER [1951ab]. Though the latter's "deduction of the magnitude of the charge is very indirect" [WORMELL, 1953], both investigations seemed to confirm the observations of Workman and Reynolds that the process of freezing of super-cooled water produces strong negative charges in ice. Measurements in aircraft or with fast rotating field mills, however, are subjected to the generation of spray electricity [STIMMEL and Others, 1946] and are, therefore, not entirely conclusive.

KUMM [1951] found that conditions leading to splinter formation were strong temperature gradients within a layer of rime formed from dendritic crystals. The ratio between positively and negatively charged splinters was 7.6 to 1, whereas the ratio between all neutral splinters to all charged splinters was 10 to 1. The average charge carried by a positive splinter was 7×10^{-16} coul. The author considered the process of minor significance for the generation of charge in thunderstorms. Whereas strong temperature differences within hydrometeors are certainly no source of splinter formation in thunderclouds, they may be produced by collision between hydrometeors. Nothing is known, however, on the electrical gain of such a process and whether this process would be identical with the mechanism of frictional electricity. This frictional process, in the physical sense, has been investigated by KUNKEL [1950], but his results were not encouraging for an application to thunderstorm electricity [WORMELL, 1953]. CHALMERS [1952] found in experiments with snow flakes that the larger particle was negatively charged, but purposely avoided any conclusions regarding thunderstorm charge generation.

Investigations using an experimental set-up analogous to Workman and Reynolds' [GILL and ALFREY, 1952ab] showed that during the freezing of distilled water the ice acquires a positive charge and the water a negative one, an effect just opposite to Workman and Reynolds' findings.

The "wet hailstone stage" with water splashing off is considered the active particle for charge generation and separation [REYNOLDS, 1953], but it should be remembered that nothing is known of the blow-off mechanism and that lightning and thunder also occur in clouds from which completely dry soft hail particles (graupel) are being discharged. This may cast some doubt on the applicability of the Workman-Reynolds effect which requires the wet hailstone stage.

H. Radar and cloud physics research--In the period covered by this report, radar was used in two basically similar, but operationally different, ways: (1) to detect that point within a cloud where cloud droplets initially grow to sizes where they will give a detectable echo, and (2) to depict the outline and extent of the rain core or precipitation area within clouds and to follow the changes of these rain cores or precipitation areas in space and time.

Regarding radar meteorology, **BATTAN** [1952] reported on the analysis of data from a radar set AN/TPS-10 in order to study the processes of precipitation initiation in natural convective clouds. He showed that about 50 pct of all echoes first appeared at temperatures warmer than 0°C, and that about 50 pct of those echoes which grew more than 5000 ft after first detection also appeared at temperatures exceeding 0°C. Using RHI data taken at intervals of about two minutes, the time history of precipitation in clouds was studied. Studies of the relation of height to time showed that the average rate of rise of the radar echo after initial detection was about 900 ft per minute, a value much too great to allow ice crystals to fall from the upper cooler portions of the cloud into the warmer regions below. Battan concluded that in middle latitudes precipitation frequently forms through a process involving only the liquid phase of water.

A similar conclusion was published earlier by **REYNOLDS** and **BRAHAM** [1952] who studied the published data of the Thunderstorm Project. A compilation in the final report of the Thunderstorm Project showed that the initial formation of a detectable radar echo in cumulus clouds over Ohio occurs at an average temperature of approximately 0°C. The authors concluded that it was impossible for an echo to form at such low temperatures through an ice crystal process. Similar data for New Mexico, however, indicated the initial radar echo to form at temperatures considerably colder than 0°C, so that the ice crystal process could not be ruled out as a possible process for the formation of precipitation there.

A theoretical study of the growth of precipitation particles in cumulus clouds made by **WEXLER** [1952a] and based on the premise that precipitation is initiated through the ice phase, when compared with observations of the initial radar echo, showed general agreement between the theory and the observations in New Mexico (data of Workman and Reynolds). The theory, however, did not agree with observations taken by the Thunderstorm Project in Ohio.

WEXLER's [1952b] theoretical study of the formation of horizontal bands of precipitation elements at above freezing temperatures assumes that under suitable conditions a layer of graupel could develop at heights where the temperatures are -12 to -17°C. Thus it is possible to explain the observations of the upper radar band reported by **BOWEN** [1951]. **BROWNE** [1953] presented critical remarks to Wexler's study. The structure and growth of cirrus filaments were explained by **ATLAS** and **PAULSEN** [1952] making use of the slope of these filaments as revealed by radar. They concluded that the observations demanded a "generating element" (such as an atmospheric wave) moving faster than the wind. The mechanism of the operation of this generating element and the mode of formation of the precipitation particles were not specified, however.

CUNNINGHAM [1952] analyzed a cyclonic storm over eastern United States making use of synoptic meteorological information and detailed radar information obtained from a B-17 and from ground radars operated by the MIT Weather Radar Research Project. An attempt was made to relate the synoptic meteorological aspects of the storm with the microphysical processes of precipitation formation. Numerical integrations of the various equations of precipitation particle growth were carried out for three different cloud structures found in the cyclonic area. In the region of the isallobaric low, 90 pct of the precipitation particle growth was due to snow agglomeration and condensation on the melting snow cluster. The altocumulus and tenuous cumulus congestus associated with the disturbance at moderately high levels supplied most of the water for the growth. In an area of steady precipitation, one-third of the particle growth was due to sublimation on snow crystals at moderate heights while two-thirds were caused by coalescence in the low cloud layers. In a showery area south of the center, one-fifth of the growth was found to be due to ice crystal accretion in altocumulus clouds and four-fifths to coalescence in the low level dense water clouds.

JONES [1952] verified results of the relation between turbulence and radar echo. Turbulence increased slowly with height half way up a cumulonimbus cloud and thereafter remained at or near its maximum value. In the top third of the cloud, the turbulence decreased with height to a minimum value near the top. Large gusts were more frequent in clouds of greater vertical extent. Considerable turbulence was found in clouds which failed to produce a radar echo, however, the larger and more dangerous gusts were found in clouds which produced heavy radar echoes.

MARSHALL and **GUNN** [1952] studied measurement of snow by radar while **PLANK, ATLAS,** and **PAULSEN** [1952] explored detection capabilities at different wave lengths.

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A VARIABLE, CIRCULAR-ARC RULE; AN AID IN CONSTRUCTING STEREOGRAPHIC PROJECTIONS

Robert E. Wallace, Bernard Fried, and John Guptil

A drafting instrument which provides a ruling edge for drawing arcs of circles the radii of which are unusually long is described. A complete range of arcs of different curvature, within the limits prescribed by the construction of the instrument, are obtainable.

This instrument was developed originally to allow accurate construction of circular arcs of very low curvature, which are difficult or impossible to draw with an ordinary compass, in constructing stereographic projections. It is apparent, of course, that numerous other applications are possible. To satisfy the authors' needs, a relatively small model was constructed, but the same general construction could be used in larger models.

The circular curve of the ruling edge is obtained by applying pressure on an elastic rod as shown in Figure 1c. If equal pressure is applied at each of the four points, A, A′, B, B′, the arc formed between B and B′ will be the arc of a circle. Proof of the validity of this principle can be found described by LAURSON and COX [1947].

Figures 1a and 1b show the essentials of construction and should be nearly self-explanatory. The cam, when rotated, applies pressure to the two lever arms which are pivoted at opposite ends of the instrument, thus transferring pressure evenly at two bearing points to the flexible bar which forms the ruling edge. Opposing forces between the fixed bearing points at the ends of the instrument and the two movable bearing points on the lever arms deform the flexible bar and an arc of a circle is formed between the two movable bearing points.

As shown in Figure 1b, the knob which turns the cam is calibrated in inches of radius of the circular arc formed. This calibration was developed by determining the radius from the ratio of arc height to segment length by the formula $r = (h^2 + y^2)/2h$ where r = radius, h = arc height, and y = half of the segment length. Calibration, of course, could be in a variety of other units.

The bar spring which forms the circular arc was made of a 1/8-inch square brass rod, but other materials undoubtedly could be found which would serve as well or better. The cam was made of brass and the lever arms of 1/8-inch steel. The housing was made of aluminum.

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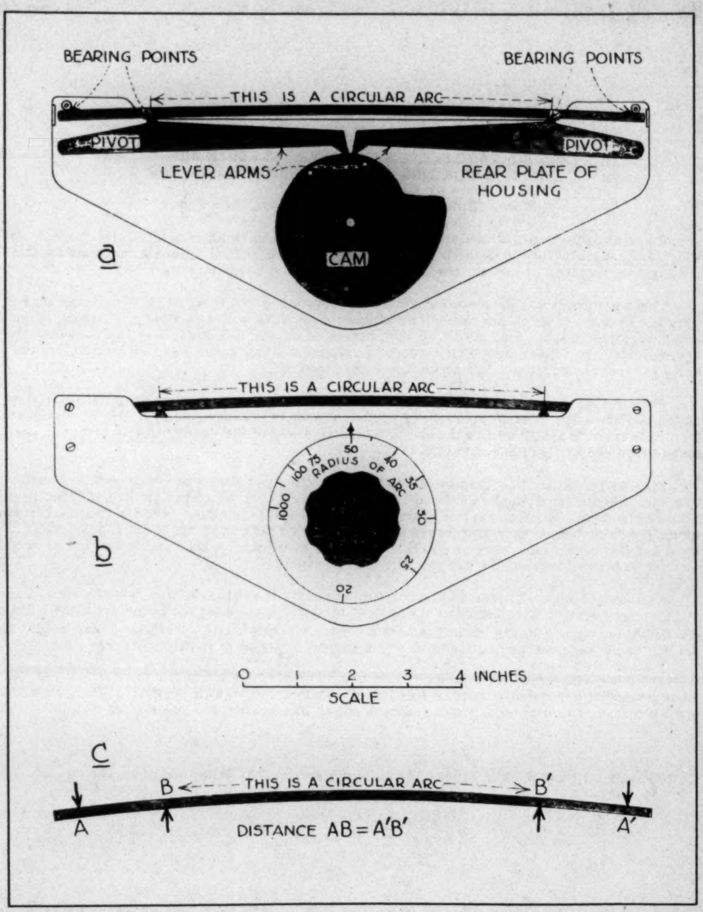
BEARING POINTS
BEARING POINTS
THIS IS A CIRCULAR ARC
PIVOT
PIVOT
LEVER ARMS
REAR PLATE OF HOUSING
CAM
a
THIS IS A CIRCULAR ARC
50
40
35
30
25
20
75
100
1000
RADIUS OF ARC
b
0 1 2 3 4 INCHES
SCALE
c
B
THIS IS A CIRCULAR ARC
B′
A
A′
DISTANCE AB = A′B′

Fig. 1--Diagram of variable circular-arc rule: (a) instrument with front plate of housing removed to show moving parts (shaded); (b) instrument with front plate in place; and (c) diagram of principle by which circular arc is produced; forces at A, A′ and B, B′ are equal in magnitude

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THE EFFECT OF WATER TEMPERATURE UPON THE CALIBRATION OF A CURRENT METER

A. D. Robson

(Published by permission of the Deputy Minister, Department of Northern Affairs and National Resources, Canada)

Abstract--Four ratings of a current meter made over a wide range of water temperatures gave no indication of change in calibration within the limits of accuracy of the ordinary current meter rating table.

Introduction--In 1952 a query was received concerning the effect of water temperature upon the calibration of current meters, particularly at low water speeds. This query was initially raised by E. C. Schnackenberg of the Dominion Soil Conservation Council, Wellington, New Zealand, and was referred through L. G. Straub, St. Anthony Falls Hydraulic Laboratory, and the U. S. Geological Survey to the Government of Canada Current Meter Rating and Experimental Station at Calgary, Alberta. At this station current meters are rated in an outdoor tank in which a wide range of water temperatures occurs seasonally.

A search of pertinent literature produced no information on this subject. As the current meter is used widely to obtain records of stream flow a series of tests under a wide range of water temperatures was arranged. The U. S. Geological Survey furnished a Type AA low-velocity current meter for use in the tests.

Purpose of experiment--The purpose of this work was to determine the effect of variation in water temperature upon the calibration of a current meter, particularly at low water velocities.

Apparatus--The following equipment was used: (1) U. S. Geological Survey current meter WR-21619-L, Type AA-Low Velocity; (2) current meter rating equipment at the Government of Canada Current Meter Rating and Experimental Station; (3) one 30-lb lead sounding weight; and (4) one Fahrenheit thermometer.

Procedure--Ratings were made only on days when there was no wind affecting the water in the tank. Before each rating the water was agitated by dragging a plank through it with the rating car in order to break up any threads of current that might have existed in it due to wind. A period of 45 minutes was then allowed for the water to become still.

The meter was dismantled and all friction parts were cleaned and re-oiled with a wipe of very light oil. It was reassembled and the contact was set to give a light wipe on the cam. The wheels of the rating car were cleaned with a wire brush to remove any pieces of dirt that might affect the smoothness of operation at very low velocities. Water temperatures were taken at both ends and at the center of the tank and the mean of the three figures was recorded. The meter, in conjunction with a 30-lb lead weight, was suspended by a free wire from the rating car.

Each rating consisted of runs both up and down the tank at approximately the following speeds: 0.15, 0.25, 0.50, 0.75, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 6.0, and 7.0 ft/sec. In all ratings, two runs at a velocity of 0.15 ft/sec or less were made. Any runs which appeared doubtful in any way were rerun. Four ratings were made at water temperatures varying from 62.5 to 36.9°F. After each rating the meter was thoroughly cleaned and re-oiled.

The results of the ratings were reduced to feet per second and revolutions per second and plotted on graph paper at a scale of one revolution per second = 10 cm and one foot per second = 5 cm. Each rating was plotted on a separate sheet of paper and from the graphs the table shown below was compiled.

Observations--Table 1 shows a comparison of the four ratings made. Rating 1 is used as the master rating and the others are compared to it.

Table 1--Comparison of the rating

Rating	1	2		3		4	
Water Temperature (°F)	62.5	55.6		44.3		36.9	
Rotation	Velocity	Velocity	Deviation from 1	Velocity	Deviation from 1	Velocity	Deviation from 1
rev/sec	ft/sec	ft/sec	ft/sec	ft/sec	ft/sec	ft/sec	ft/sec
0.05	0.14	0.14	0.00	0.14	0.00	0.14	0.00
0.50	1.13	1.13	0.00	1.13	0.00	1.13	0.00
1.00	2.23	2.23	0.00	2.24	0.01	2.23	0.00
1.50	3.33	3.33	0.00	3.34	0.01	3.33	0.00
2.00	4.43	4.43	0.00	4.43	0.00	4.43	0.00
2.50	5.53	5.53	0.00	5.53	0.00	5.53	0.00
3.00	6.63	6.63	0.00	6.63	0.00	6.63	0.00

Discussion--Ratings 1, 2, and 4 are identical throughout the entire range of the velocities run and within the limits of the accuracy of the tests, that is, to two decimal places. Rating 3 deviates slightly from the master rating at two feet per second and rejoins it at four feet per second. This variation is only 0.01 foot per second at its maximum and could be due to inaccuracy in the rating. There is no indication of this shift from the master curve being a trend with decrease in temperature since rating 4 at the lowest temperature agrees with rating 1 entirely. This fact backs up the assumption that the variation in curve 3 is due to some inaccuracy. In the low velocity range from two feet per second down to 0.15 foot per second, there is no discernible variation in the calibration with change in temperature.

Conclusion--Within the limits of accuracy of the ordinary current meter rating tables which give feet per second and revolutions per second to two decimal places, there is no indication of change in calibration with variation in water temperature over a velocity range of 0.15 to 7.0 feet per second and a temperature range of 62.5 to 36.9°F.

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DISCUSSION OF

"ARTIFICIAL ROUGHNESS STANDARD FOR OPEN CHANNELS"
by A. R. ROBINSON and M. L. ALBERTSON

[Trans., v. 33, pp. 881-888, 1952]

Ralph W. Powell (Department of Mechanics, Ohio State University, Columbus, Ohio, received April 24, 1953)--The need of fundamental studies on the resistance to flow in open channels is becoming more generally recognized, and this paper is a valuable contribution to the problem. The fact that each paper that has appeared in the last few years comes to somewhat different conclusions points up the need for still further research in this field. At any rate it has been pretty well proved that the formula proposed by the writer in 1950 is not the final answer. On the other hand, the eminent authority THIJSSE [1951] has agreed that these efforts are in the right direction.

It is only at a few minor points that the writer would criticize this excellent paper. It would seem that 14 ft was much too short a length for an experimental channel of this sort, even when the six-foot entrance section is taken into account. It is very difficult in so short a flume to be sure that uniform flow has been established, and it is hard to determine the slope accurately.

Unfortunately there is no general agreement on the precise meaning of Reynold's number for open channels. The authors have taken it as $VR\rho/\mu$, while the writer used four times that value so that the same formula could be used for pipes. This affects Eq. (6) and the points and line at the bottom of Figure 4. These should be moved to the left to values one-fourth of those shown.

In Figure 1 and Eq. (10) the shearing force is made to depend on $\Delta\gamma$, the difference in specific weight of air and water. This is theoretically correct, but since air weighs only about 0.0765 lb/ft^3, the difference between γ and $\Delta\gamma$ is small. Also the question arises as to whether the values ordinarily tabulated for the specific weight of water are not based on the weight as weighed in air, so that they actually are values of $\Delta\gamma$ rather than γ.

The title of the paper by Hunter Rouse in References should be Evaluation of Boundary Roughness.

It is to be hoped the Fort Collins Laboratory may continue its research on this problem.

Reference

THIJSSE, J. TH., Discussion, Trans. Amer. Geophys. Union, v. 32, pp. 609-610, 1951.

Walter Rand (Iowa Institute of Hydraulic Research, State University of Iowa, Iowa City, Iowa)--The laws governing open channel flow over rough surfaces are not yet fully known, and the authors' investigation is a welcome supplement to the knowledge in this field. However, as the authors have pointed out, the flow as investigated was not fully two-dimensional, and the writer believes that the coefficients in (32) are somewhat modified by this fact. In order to obtain a better interpretation of the results of this investigation, a short analysis is necessary.

The values of $C/\sqrt{g}$, shown in Figure 3, are computed from the Chezy equation in the form (indicated in a letter from the authors)

$$C/\sqrt{g} = Q/Bd\sqrt{gds} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (33)$$

This equation shows, that for a given depth and slope the reduction in Q by the side walls would also reduce $C/\sqrt{g}$. Similar investigations made by the writer show that the effect of the side walls starts with the lowest practicable depth. This is why the flow in the authors' investigation could not be strictly two-dimensional for the values of d/a between 3.3 and 10. There would be, rather, a gradual decrease of Q and consequently of $C/\sqrt{g}$ (33) with increasing d, leading to $K_2 = 4.7$ in (32).

From Figure 3 it can be seen that it is possible to pass through the points with $d/a < 5$ a line for which the slope K_2 is about 5.75, the corresponding coefficient in (3). Also, if the discharge is increased about seven per cent, to compensate for the influence of side walls, the points for which $d/a = 17$ would also fall on the line of 5.75 slope for the points of $d/a < 5$. Corrections of this magnitude for the effect of the side walls have been obtained by the writer.

The measurement of the depth d, taken arbitrarily from the bottom, has another effect on the results. The points in Figure 3 form in this case a line with maximum slope possible (according to (33)). However, a level somewhere between the top and bottom of the roughness elements, from which to measure d, might be preferred, if the velocity distribution, computed with this level, would correspond to the logarithmic law. As the velocities were not measured in this investigation, this level could not be determined. Because d is measured from the bottom, the coefficient K_2 might have a slight increase, compensating for the reduction of Q by the side walls.

From this brief discussion it is logical to conclude that in the case of truly two-dimensional flow and of d, measured from the level that is used to have the computed velocity distribution corresponding to the logarithmic law, the coefficient K_2 may be equal to the value of 5.75 in (3).

A. R. Robinson and M. L. Albertson (Soil Conservation Service and Colorado Agricultural and Mechanical College, Fort Collins, Colo., Authors' closure)--The comments by Powell and Rand add materially to the value of the paper and, therefore, are very much appreciated by the authors.

Powell points out that "14 ft was much too short for an experimental channel of this sort." The authors agree that it is much shorter than is desirable, but physical conditions within the laboratory made it extremely difficult to have the channel longer. Therefore, an analysis was made of the objections to a short experimental channel in order to overcome these objections as much as possible by special techniques.

The objections which were considered included: (a) the backwater curve (either M_1 or M_2) beginning at the downstream end of the channel influences the depth of flow a great distance upstream; (b) the usual "end-gate" or sluice-gate type of downstream control causes a non-uniform flow pattern for several depths upstream; (c) the vertical profile of the mean velocity distribution is not established for a considerable distance downstream from the entrance to the channel; (d) the turbulence profile is not established for a considerable distance downstream from the entrance; and (e) a considerable distance of perfectly uniform flow is needed to measure accurately the depth of flow and the slope.

To overcome the difficulty with backwater curves, the depth was measured along the channel with various degrees of control at the downstream end. Care was taken to adjust the control so that both M_1 and M_2 curves were obtained. By means of interpolation a rather exact setting of the control was determined, and the normal depth and the slope were accurately obtained. The control was made of narrow slats placed vertically in the channel so that the upstream disturbance to the flow pattern was held to a minimum.

At the upstream end of the channel, extremely large roughnesses were placed on the floor of the entrance section to help establish the profiles of the mean velocity and the turbulence. By this means, adjustments in upstream baffles could be made until the profile of mean velocity is established as desired. However, because of lack of measuring devices, the profile of the turbulence could not at that time be determined except quantitatively by visual inspection.

By the procedure described, an attempt was made to minimize the effects of the upstream and downstream ends of the channel and thereby increase the usable length of the measuring section. The degree of success obtained by this technique is indicated by the manner in which the experimental points plot in Figure 3. The scatter of these points may be due in part to the short length of the channel, but the systematic correlation obtained for different baffle sizes indicates that the errors are not great.

To compute Reynold's number $VR\rho/\mu$, the authors recalculated the data from Powell, so that Figure 4 is properly plotted. R was replaced by d since the width was assumed to be infinite.

Presumably, the specific weight γ of water was originally evaluated in a vacuum so that for an accurate evaluation of γ in open channels the specific weight of air must be subtracted, hence $\Delta\gamma$. However, the error involved is approximately 0.1 pct, so that the influence of air can safely be ignored for most studies.

Rand has remarked that the flow may not be two dimensional which could modify the coefficients in (32). As discussed in the original paper, it is quite possible that side effects are important for values of $d/a > 9$ or 10. However, for values less than nine there is no significant difference between the data for $a = 1.0$ inch and $a = 0.5$ inch; and yet the channel is effectively twice as wide for $a = 0.5$ inch as for $a = 1.0$ inch. Therefore, the authors remain convinced that the side effects are insignificant and the flow is effectively two dimensional.

Because of the scatter of the data, however, it is possible to approximate the data with a line having a slope such that K_2 is 5.75. In fact this

$$C/\sqrt{g} = 5.75 \log d/a + 0.5 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (34)$$

line fits the data almost as well as (32). In view of its significant similarity to (3), the authors recommend (as does Rand) that the foregoing equation be used instead of (32) as originally recommended.

It is interesting to note that by proper adjustment of the roughness, it would be possible to develop an equation having nearly any desired value of K_1. In fact K_1 could be made equal to zero for simplicity.

DISCUSSION OF

"WATER QUALITY PROBLEMS IN CALIFORNIA"
by HARVEY O. BANKS and JACK H. LAWRENCE

[Trans., v. 34, pp. 58-66, 1953]

Raphael G. Kazmann (Fricke and Kazmann, Consulting Engineers, Stuttgart, Ark.)--As the authors point out, the major unsolved problem in California is: How can the perpetual usability of ground-water basins as reservoirs for fresh water storage be assured? This implies that the ground-water basins, when used for storage of surplus surface waters, must be alternately emptied and filled, and that an economical method to accomplish this must be devised. If these requirements cannot be met, the fundamental conclusion, "... that the State's water resources ... may be adequately regulated ... to meet its probable water requirements without importation of water from a source outside the State of California ..." may be seriously in error.

The authors mention "overdraft conditions" as leading to the degradation of ground-water quality; that is, the lowering of pressures in pumped aquifers which cause movement of water of inferior quality into the usable water-bearing formations or parts thereof. It is implied that the cure for the increase in mineralization is the cessation of "overdraft."

It should be pointed out that unless the piezometric surfaces in pumped aquifers are systematically and substantially lowered when it is necessary to use the aquifers, there will be no storage volume available for use during a "wet" period when surplus surface waters can be used to replenish the aquifers. Therefore overdraft conditions, far from being unusual, must be considered as part of "standard operating procedure" in ground-water basin utilization. Methods must, therefore, be devised to prevent movement of undesirable water into fresh-water aquifers. Among such methods are the sealing of abandoned wells, prohibiting the connection of aquifers containing waters seriously dissimilar in nature, establishing well fields to pump mineralized ground water in order to protect the fresh water from contamination, establishing well fields for artificial recharge and to maintain fresh-water barriers against salt-water intrusion. Perplexing questions of engineering and law, not even hinted at in the paper, will have to be solved in the course of achieving the full utlization of ground-water basins as storage reservoirs for surplus surface waters.

The writer concludes that solution of the water-quality problems, which are so well described in this paper and listed in its summary, is dependent upon the development of economical large-scale artificial recharge through wells or other structures. Only after such a procedure has been soundly established on an engineering basis will it be possible to control movements of mineralized ground water.

It may be fair to conclude that the water resources of California (and most of the other states) cannot be utilized to the maximum extent unless such a method is developed. The method must be effective in the majority of geologic situations, and especially in artesian aquifers which have been wholly or partly dewatered.

In a very important sense this fine paper spells out the reasons why development of a sound, practicable, and economical method of artificial recharge should now be the first order of business for workers in the field of hydrogeology. The authors are to be commended for stating these reasons so forcefully.

DISCUSSION OF

"USE OF WATER BY NATIVE VEGETATION VERSUS GRASSES AND FORBS ON WATERSHEDS"

by F. J. VEIHMEYER

[Trans., v. 34, pp. 201-212, 1953]

Bernard Frank (U. S. Forest Service, Washington, D. C.) and Leon Lassen (Consulting Hydrologist, Falls Church, Va., received June 26, 1953)--The author refers to the importance of converting (to grass) brushlands of potential value for livestock grazing (p. 201). It would be helpful if he could have presented criteria for determining this value in such terms as (1) the ability of converted lands to maintain adequate forage production under grazing use, and (2) ability of their soils to withstand high intensity rainfall under grazing. Since his experiments did not involve determinations of the actual effects of grazing, is it possible that the results may not necessarily apply to the conditions which might be expected under such use?

One stated object of the experiment is to determine vegetative succession (p. 202). Have the observations been carried far enough or so designed as to accomplish this objective in an adequate manner? For example, it is possible that successional trends might be quite different under grazing use (with or without reseeding) than under burning alone. This question seems important in view of the fact that brush conversion by burning (or other means) usually represents the initial step in developing forage for livestock use, and under such conditions the course of succession may be influenced by additional factors not discussed in the article.

Is the assertion fully warranted that the moisture storage of the soils under study is unimportant as a factor in flood runoff (pp. 202-203)? An available soil-storage capacity of six inches prior to flood occurrences may not be great, yet its reduction by half might make a considerable difference in the time and magnitude of flooding. To illustrate, Table 2 shows that the excess water in the burned Button Canyon plot at the end of the ninth year amounted to 2.4 inches as against only 0.1 inch at the end of the first season (p. 203). It is usually accepted that flood magnitudes are roughly proportional to the volume of surface and subsurface runoff. In that case, the reduction of 2.3 inches in available storage indicates probabilities of damaging flood occurrences under such conditions. Thus, instead of only 1.6 inches runoff, as under the unburned condition, an eight-inch rain would produce 3.9 inches, representing a considerable increase in the volume of flooding. Similar observations apply to the burned Holland Plots (2.7 inches excess water) and to the burned Cold Fork Plots (1.8 to 3.6 inches flood runoff). Again, in the case of the Monterey Plot 2, whereas an eight-inch rain on the unburned plot would not suffice to fill the storage capacity, after the first year's burning such a rain would produce 1.2 inches of runoff. These data do not appear to support the statement that flooding is not a factor in the soils in question.

The author reasons that burning does not impair the absorptive capacity of the soil because (1) the soils of the burned plots were wet as early as those of the unburned plots, and (2) experimental evidence indicated only slight differences in runoff between the two soil conditions (pp. 207, 212). This line of reasoning seems difficult to follow. Similar results as those obtained by the author would be obtained even where soils differed very materially in water absorption (infiltration capacity) characteristics, so long as the rates of rainfall are less than the lowest infiltration capacity of all the several soils tested for this relationship. Under such circumstances no other results can be expected. Thus if two soils, one having an infiltration capacity of 1.0 inch/hr and the other 0.5 inch/hr, are subjected to a rain whose intensity does not exceed 0.4 inch/hr, the water will readily penetrate in both cases. Such a relatively low intensity actually masks the fact that one soil can absorb water twice as fast as the other.

H. C. Fletcher and L. R. Rich (Southwestern Forest and Range Experiment Station, Tucson, Ariz., received August 6, 1953)--Results of studies at Sierra Ancha Experimental Watersheds [RICH, 1951] (located in Tonto National Forest in central Arizona), comparing water use by grasses and shrubs, agree in general with the conclusion reached by Veihmeyer that the establishment of grasses and forbs on areas previously occupied by shrubs should result in additional moisture. The writers are in general agreement with the views expressed. The few comments that follow are intended to interpolate a few items of correlative interest and to give a more geographical breadth to the subject.

In the Southwest, chaparral seldom forms a complete canopy. Grasses and other lesser vegetation occupy the interspaces. Where this cover is absent or decreased, erosion is usually present in the intershrub spaces and assumes serious proportions in the more erodible soils. Thus from the standpoint of excess water, forage production, and erosion control, perennial grasses are generally superior to chaparral.

Water savings on watersheds bare of all vegetation are largely hypothetical because no watershed can be maintained bare of all vegetation for extended periods; some type of vegetation will grow even under extremely adverse conditions. The extent to which the chaparral plants occupy sites and extend their influence under favorable conditions is illustrated in Veihmeyer's article where he points out that it was difficult to eliminate transpiration; that roots from outside the plot interfered with soil-moisture samples even in the center of the sterilized plot. The extensive root system of chaparral used water far beyond the crown area and prevented establishment of grass along the border of a cleared plot (Fig. 15). Consequently it is not a question of whether vegetation is desirable on an area, but rather the type of vegetation that would be most beneficial for all types of use and still maintain the resource.

In addition to the relative amounts of water required for growth of a particular type of vegetation, the time of the year that plants use water affects water yields. Vegetation that uses water during high water-yielding periods when the soil moisture is above field capacity, consumes moisture that may otherwise be available for streamflow. On the other hand, if a type of vegetation can be maintained that makes its growth after the period of excess moisture drain-out and after the soil moisture drops below field capacity, then that use should interfere least with water yields because it would use some moisture that would otherwise be evaporated, other things being equal.

Winter precipitation at the Sierra Ancha Experimental Watersheds occurs in about the same winter months as in some parts of California. In addition, a significant amount of precipitation occurs in the summer months of July and August and some years in September. Drought in April, May, and June, and usually in at least part of the fall months, September, October, and November, allows for a division of the annual precipitation into winter and summer periods. Approximately 65 pct of the year's precipitation falls in the winter period, considered as October through May, and 35 pct in the summer period, June through September. Nearly all of the streamflow at the experimental watersheds occurs during the winter. It is in excess of 92 pct of the annual total where the watershed area is steep, where the drain-out is rapid, and where no perennial flow occurs. Where perennial streamflow occurs, the percentages of winter water yield are somewhat lower since part of the summer flow is fed by stored winter moisture.

Salt River, which provides the water for almost one-half of Arizona's population, yields 82 pct of the annual total during the winter period and 18 pct during summer, with part of the summer base flow being fed by residual winter precipitation.

Monthly precipitation and streamflow for Salt River, expressed as a per cent of the annual total, are shown in Figure 16. As will be noted, most of the year's total streamflow occurs in March, April, and May, while the high rainfall in July and August yields relatively little streamflow. Contrasted with streamflow are the results of water use by different species of plants grown in small lysimeters which are shown at the top of Figure 16. The solid parts of the graph represent the period of major or heavy use and the dotted parts of the graph the periods of reduced water use.

Evergreen chaparral species used some water most of the year, with a period of heavy use in the spring and late summer. Snakeweed, a half-shrub, and filaree, a winter annual, also have a period of heavy water use in the spring, when most of the water yield occurs in Salt River. The grasses considered in this study are the native grasses of the area and are all summer growers. They are dormant during the winter and spring period when most of the water yield occurs. Thus they use less water during the high water-yielding period with the least interference with the major period of water yield in the spring when soil moisture is above field capacity and surplus moisture appears as streamflow. Comparing the periods of the year when water yields occur and the periods when water is available for growth by different types of plants indicates why chaparral, which decreases the soil moisture prior to the beginning of the winter rainy season, competes for water that may otherwise appear as water yields.

Since no watershed can be kept bare of all vegetation, the type of vegetation at the Sierra Ancha Experimental Watersheds that uses least water during the high water-yielding period and interferes least with water yields is the summer-growing grasses. On the other hand, deteriorated watershed vegetation, such as snakeweed, winter annuals, and evergreen shrubs, not only use larger quantities of water but also this use occurs during the period of high water yields to streams.

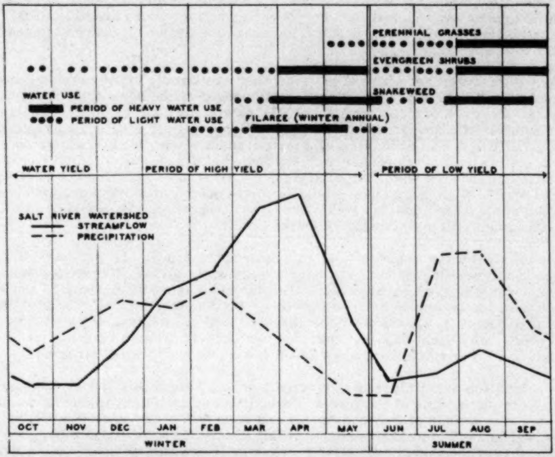

Fig. 16-- Relation of periods of water use by plants to precipitation and streamflow

However, there is another side to the question of vegetation removal. When the vegetal cover is eliminated, as is outlined in Veihmeyer's article, some thought must be given to replacing that cover with a species of vegetation that will provide protection to the soil resource. Some soils are greatly damaged by the removal of the protective vegetation, to say nothing of the erosion and flood hazards that may result. These factors have to be considered along with any removal or change in vegetation cover. We recognize the intent of the article is to show how shrubs deplete the moisture available for streamflow; but we feel that some qualifications should have been made as to conditions, locations, and limitations. Certain conditions in California and in Arizona, as the data show, may favor the removal of brush, but we do not feel that such recommendations should be made general for all conditions. Brush may be the most practical cover that can be grown under many conditions. To destroy it would be folly. Under other conditions such as are described, clearing brush may be desirable and offers a means of increasing water supplies, but is not a panacea for all the brush problems, as the article leads one to believe.

The three paragraphs preceding the summary of Veihmeyer's paper present data of "transpiration losses of moisture compared to evaporation." This comparison is under unnatural conditions and would probably never apply to any natural area that contributes water to streamflow. If practical comparisons were desired, why was not the rainfall allowed to fall on the bare tank or why was not water added to the bare tank at the same time water was added to the tank containing the tree? If some such method had been used, it seems to us the results would have been closer to "comparative."

Maximum loss of water from bare soil occurs immediately after an application of water. VEIHMEYER [1927] earlier pointed out, "These rapid losses by evaporation from the soil surface" (bare) "which immediately followed irrigation and which constituted about one-half of the total loss from this cause within a period of about three months occurred before the surface of the soil was in condition to be properly cultivated." Other investigators [MEYER, 1928] point out that evaporation from bare soil depends on "evaporation opportunity" and that immediately following a rainstorm the rate of loss from land areas approximates the rate of loss from shallow water.

In areas such as the Southwest, where summer rainfall is a significant part of the total annual precipitation (about one-third at Sierra Ancha Experimental Watersheds), the evaporation opportunity may become a big factor. Most of the storms are of small total quantity. For example, at

4600-ft elevation, 84 pct of the rainfall occurred as storms of less than one inch total quantity in a 24-hr period, and 48 pct less than 0.3 inch. These small storms wet only the surface of the soil and increase the evaporation opportunity. Under these conditions evaporation from bare soil is actually a large proportion of the summer rainfall, approaching an amount almost equal to the total summer rainfall at 2500-ft elevation and 92 pct at 5100 ft, as measured from small lysimeters.

These data considered with the fact that it is impossible to maintain watersheds bare of all vegetation, strengthen the management concept of the desirability of evaluating the available moisture supplies as to their most desirable uses and then utilizing the moisture to grow a protective plant cover which would interfere least with these uses.

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V. L. Bosazza (Ave. Republica, Lourenco Marques, Mozambique, Portuguese East Africa, received September 23, 1953)--The amount of water used by different types of vegetation and the question of altering the vegetal cover of vast tracks of virgin country in southern Africa is a very great problem. There is no doubt that the removal of vast areas of bush and the resulting landscape of grass or crops causes upcurrents of air. This can be very well experienced when flying over the greater part of the Union of South Africa, in light planes at elevations of 500 to 2000 ft above the ground. This may cause irregular and erratic precipitation locally. Accurate work of the nature carried out by Veihmeyer and by THERON [1947] in South Africa is of very great importance. The importance of this work in a study of Africa is greater than is generally considered. Table 3 shows the distribution of rainfall, in various parts of South Africa, and what part the type of vegetation can play in the economic use of rainfall.

Table 3--Hydrologic balance of various catchment areas in South Africa

Catchment	Type^a	Percentage of total annual precipitation		
		Pumpage or spring flow	Runoff	Transpiration-evaporation losses
Magaliesburg	d	0.13	4.6	95.3
Olifantsfontein	do	6.5	2.6	90.9
Olifantsfontein	do	8.2	2.6	89.2
Zuurbekom	do	4.0	2.3	93.7
Maloney's Eye	do	10.0	5.9	84.1
Pretoria Fountains	do	23.8	5.7	70.5
	do	10.7	5.7	83.6
East Rand	sh	3.0	8.5	88.5
Pretoria	sh and d	2.0	nil	98.0
Johannesburg	s and q	2.5	4.2	93.3
Johannesburg	s and a	6.5	5.5	88.0
Halseton	s and di	2.4	3.2	94.4
Rooiberg	s and sa	0.58	5.7	93.7

^{a}d, mainly diabase and syenite; do, dolomitic limestones; s, shales; sh, Karroo shales; q, quartzites; a, andesites; di, dolerite; and sa, sandstones.

It is evident from these values that only the dolomitic limestones show marked infiltration differences from the other rock types. The shales and andesites, and quartzites and shales of Johannesburg dip at angles as much as 40°, yet show little difference in infiltration from other shales and other igneous rocks. The Rooiberg sandstones are very flat rocks and the apparent transpiration-evaporation loss includes at least one or two per cent of the total annual rainfall in underground water not pumped, that is subsurface drainage. This is known from boreholes drilled since these values of pumpage were obtained. The value for infiltration and runoff for Pretoria is that from a lysimeter [THERON, 1947]. The transpiration-evaporation loss is distributed between evaporation and transpiration but in what proportion it is difficult to say. For the summer rainfall areas of southern Africa, the evaporation from a free water surface exceeds the total annual precipitation by at least double. Somewhat similar values of transpiration losses have been found by

THORNTHWAITE [1946]. While I have considered that many lysimeter determinations of infiltration to underground are not applicable to large catchment areas in southern Africa, there is no doubt that the greater part of the precipitation goes to evaporation and transpiration [BOSAZZA, 1950, 1952ab].

HOYT and TROXELL [1934] came to conclusions very similar to Veihmeyer in dealing with results of change of vegetation of one of two comparable catchment areas, and in South Africa pines and eucalyptus have been blamed for decreased runoff and reduced spring flow [GEVERS, 1946]. While I accept such results in a general manner, we cannot live with complete water economy and we must use water to the best advantage. Thus we cannot have quick growing timbers and have large spring flow, mainly it must be admitted because of evaporation in the high temperature piedmonts as against useful tree growth on the cooler slopes of the mountains. In the course of time, the flow of water in a river purely for beauty sake will have to be avoided and all the water in Africa in the course of time will have to be used.

Veihmeyer's finding that appreciable savings of water can be effected by burning in order to substitute grasses or forbs must be balanced against other factors. According to AUBERT [1949], continuous burning or repeated burning often leads to the development of the iron or alumina crusts in French Guinea, the southern and northern Sudan, and in parts of Senegal. The process is noticeable in the course of 30 years. During discussions with Aubert in Paris in 1950, I had the opportunity of discussing this problem with him; and on my return to South Africa, I concluded that not only the iron and laterite crust but the lime crust and increased soil salinity can result from continuous burning. However, even more serious in the dry zones of Africa is the loss of the inorganic soil nutrients by burning [BOSAZZA, in press]. Continued observations since that date in Mozambique, Southern Rhodesia, Swaziland, and the southern part of Bechuanaland Protectorate, have led to the conclusion that a great deal of study is necessary on the subject of water usage by different types of vegetation, in relationship to what man and his animals can use. Most of the desert types of plants use very little water but on the other hand are of very little use to man or beast. The Karroo vegetation uses very little water and is readily eaten by sheep and cattle, even dairy stock of exotic origin, so it may be possible to cover Africa with a new vegetal cover, having a good water economy and leave the main part of the water to go to underground or surface storage for the growth under optimum conditions of concentrated foods. Quantitative experiments alone can solve this problem.

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F. J. Veihmeyer (University of California, Davis, Calif., Author's closure)--The purpose of my paper was to present data on the use of water by vegetation which replaced the original vegetation after burning, and not to study plant succession as such. It soon became apparent that the differences in use of water depended upon the replacement of the brush species by grasses and forbs. Information on the plant succession that did take place on the plots is given in the paper. Frank and Lassen question whether lands cleared of brush by burning, as was done in the experiments reported, have the ability to maintain adequate grazing. The number of controlled burns in California for the purpose of increasing forage production has been increasing steadily from 1948 [CALIFORNIA, 1953], and last year 181,710 acres were burned under permit. LOVE and JONES [1952] state: "Well-planned programs of brush removal by individual ranchers can change certain adaptable California brushlands into valuable grasslands that produce greater crops of meat and wool." HALLS, SOUTHWELL, and KNOX [1952] report that proper use and timing of prescribed fire is the key to a successful combination of cattle and timber raising.

The plots used in the experiment were not protected from grazing and in many of them cattle and deer did graze. Grazing and its effect upon runoff and erosion, however, was not the subject of study in the reported work, but rather the effect of brush removal by fire on the hydrology of the area.

Frank and Lassen seem to believe that the greater amount of water in storage in the burned plots at the end of the dry season in the fall would present a flood hazard. The lesser amounts of water required to prime the soil in the burned plots certainly would not all appear as surface runoff as their treatment of the data assumes. The surface runoff from the burned Button Canyon plot over the seven-year period of observation only averaged 0.17 pct of the rainfall. The infiltration capacity of the soil after being filled to field capacity is not reduced to zero; in fact, in the soils tested it was an appreciable amount as indicated in Figures 17 and 18.

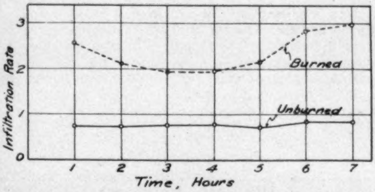

Fig. 17--Infiltration rates in inches per hour for the burned and unburned soil in the Ukiah plots; the burned plot was burned annually for seven years

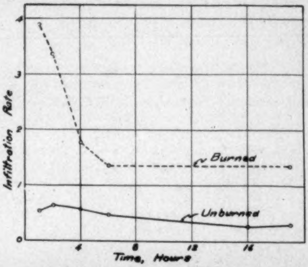

Fig. 18--Infiltration rates in inches per hour for the burned and unburned soil in the Button Canyon plots; the burned plot was burned annually for ten years

Frank and Lassen raise the question whether the intensity of rain on the plots was sufficient to indicate the difference in infiltration capacities between the burned and unburned soil. The fact that surface runoff did occur is proof that the rates of infiltration for both the burned and unburned soils were exceeded. Samples were taken from each of the plots with a special core sampler described by DONEEN and HENDERSON [1953]. The sampler utilizes a paraffined cylindrical carton into which the soil core is forced and can be taken into the laboratory for the measurement of infiltration rates on soils with undisturbed structure. The results of the tests on the soils from two of the plots are shown in Figures 17 and 18. The infiltration rate is that per unit time at which the water entered the soil when there was standing water on the soil surface. BURGY and SCOTT [1952] tested soils from four of the plots used in my experiment, namely, Oregon Oaks, Diamond Range, Button Canyon, and Holland, in similar laboratory trials, upon which amounts of brush equivalent to 111 tons per acre were burned. In every case the infiltration rates were much higher after burning. In these trials the intensity of application is at an infinite rate since the surfaces of the soils were flooded. The objection of Frank and Lassen to my statement that the infiltration of water into the soils on the plots was unimpaired by burning is not valid.

Fletcher and Rich seem to be in agreement with the findings in my paper that replacement of brush species with grasses and forbs results in a saving of water. There is no intention to suggest that brush removal by burning is a panacea for all the brush problems. As pointed out by me and emphasized by Fletcher and Rich, it is practically impossible to keep a watershed bare of all vegetation. The effect upon the water regimen and erosion of an area, of course, will be greatly influenced by the kind of vegetation which follows burning. Bare soils without the effect of the binding power of the roots to hold the soil in place might be subject to more erosion than would occur on a vegetated area, but the point of interest is whether the replacement of woody brush species with grasses and forbs results in water economy, forage production, and erosion control. Fletcher and Rich's statement in the last sentence of their second paragraph, as well as my statements, answers this question in the affirmative.

Fletcher and Rich question the comparisons made between the evaporation from bare soil in a tank and the transpiration from a pine tree in a sealed tank. It is true, of course, that if only enough water were added to the soil to wet a depth of soil of about six inches and if evaporation conditions were high following the application, most of the water would be evaporated. On the other hand, if enough water was added at each application to wet the soil to its full depth, that lost from the six-inch depth of soil would be a small part of the total amount taken from the soil by transpiration.

In the case of the pine-tree tank, a depth of water of about eight inches was applied each time the tank was irrigated. Usually all of this water was used before another application was made. With the bare tank only a slight depth of soil would lose its moisture by evaporation. The purpose in making this comparison was to point out that the loss of moisture by evaporation directly from the soil surface is confined largely to a relatively shallow surface layer. This is clearly indicated in Figures 11, 12, 13, and 14. The water yield from a watershed with such bare soil certainly would be greater than that from a brush covered area. It is not suggested, however, that bare soils are desirable from other considerations.

Bosazza points out other factors than water savings by means of substituting grasses and forbs for brush should be considered. He believes that the removal of brush causes upcurrents of air which may affect precipitation. The effect of vegetation on rainfall, of course, has been a subject of discussion for many years. The report of the Desert Encroachment Committee of the UNION OF SOUTH AFRICA [1951] contains the following conclusion: "The Committee is convinced that with the present state of our knowledge on these matters it is clearly indicated that nothing we can do on the surface of the Earth in South Africa holds out any promise whatsoever of increasing the humidity sufficiently to influence rainfall."

The development of crusts on the soil surface mentioned by Bosazza did not occur on the plots used in my experiments even though in some cases there were more than ten annual burnings. In contrast to Bosazza's belief that unfavorable chemical changes result from burning, are the findings of WAHLENBERG [1935] that frequent burning benefits the soil chemically by slightly increasing the available supply of plant nutrients. WAHLENBERG, GREENE, and REED [1939] also report that burning and grazing did not result in serious soil degradation. HEYWARD and BARNETTE [1934] found that soils subjected to frequent fires were consistently less acid and had higher percentages of replaceable calcium and total nitrogen. BURGY and SCOTT [1952] concluded from their laboratory studies that infiltration rates of soils may be favorably influenced by the burning of certain brush species and the presence of ash on the surface of some brushland soils in two ways, namely, aggregation of soil particles and chemical changes within the soil.

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DISCUSSION OF

"CORRELATION BETWEEN PIPE FLOW AND UNIFORM FLOW IN A TRIANGULAR OPEN CHANNEL"

by W. M. OWEN

[Trans., v. 34, pp. 213-219, 1953]

Harry H. Chenoweth (Department of Civil Engineering, University of Washington, Seattle, Wash.)--HARRIS [1950] has shown that formulas for rough pipes may be derived from tests on smooth pipes. The writer has elsewhere [CHENOWETH, 1951] derived such formulas for rough pipes from the von Karman-Prandtl and Blasius smooth-pipe formulas, and has shown the close correlation of these derived formulas with the Nikuradse rough-pipe formula. This concept could be applied to the data presented by Owen.

Accepting the straight line of Figure 5, we have

$$V/\sqrt{gRS} = 5.0 + 5.42 \log [(R/\nu)\ \sqrt{gRS}]$$

and defining $V/\sqrt{RS}$ as C and $4RV/\nu$ as N_R

$$C = 33.0 + 30.7 \log N_R/C \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

for smooth triangular channels. The reader will recognize C as the general coefficient in the Chezy channel formula, $V = C\sqrt{RS}$. For rough channels, C is the relative smoothness and is a function of R/e. Harris has suggested C of a similar channel, having a hydraulic radius of unity, as a measure of the specific smoothness coefficient. This coefficient C_1 is a function of the equivalent sand-grain diameter of the roughness but not of the size of the channel. Eq. (3) can be written

$$C + 30.7 \log C = 51.45 + 30.7 \log V/\nu + 30.7 \log R$$

and when $R = 1$, $C = C_1$. Therefore

$$C + 30.7 \log C = C_1 + 30.7 \log C_1R \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

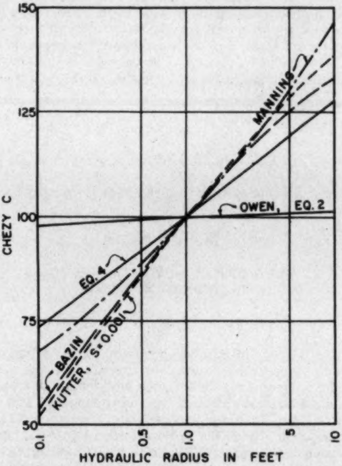

Fig. 8--A comparison of rough-channel formulas that would make C equal 100 when R equals unity for rough triangular channels. Attention is called to the fact that (4) was derived from the author's smooth-channel data only, but that it is intended for rough triangular channels. This equation is compared to other rough-channel formulas in Figure 8. Eq. (4) is based on the line drawn on Figure 5. (The author has pointed out some of the difficulties in obtaining good data for this graph.) The resulting formula has been extended to very large sizes on Figure 8 for comparison purposes. The writer is not advocating (4), but rather the general method of obtaining it.

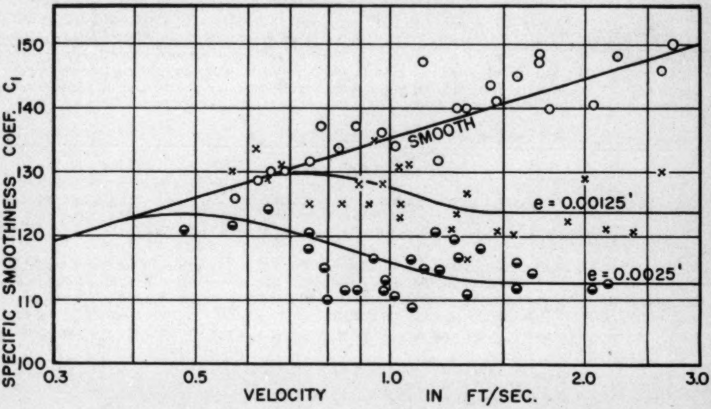

Fig. 9--Specific smoothness coefficients for the three triangular channels tested

The author's statement, "It is apparent from this diagram (Fig. 7) that the data reported herein did not agree with the Nikuradse data as well as that presented by Moody," seems rather positive in view of the lack of any evidence that the data followed a transition curve such as Moody's. As a matter of fact, Figure 9 reveals a definite "Nikuradse dip." The dip is inverted, as it should be, since the ordinate is C_1, not f_1. Since most of the rough-channel data presented were in the region of the dip, it is not surprising that the author's (2) shows such divergence from the Manning, Kutter, and Bazin formulas.

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DISCUSSION OF

"TRAP EFFICIENCY OF RESERVOIRS"
by GUNNAR M. BRUNE

[Trans., v. 34, pp. 407-418, 1953]

Albert E. Coldwell (U. S. Corps of Engineers, Tulsa, Okla.)--The use of the C/I ratio instead of the C/W ratio appears to be especially suited for use in locations such as the Texas Panhandle, where large portions of the surface area do not have any defined drainage system. Some of the surface runoff does not reach the main streams, but is impounded in large playa lakes ranging up to several hundred acres in size. In computing the watershed area for rivers traversing this type of land, it is usually necessary to divide the drainage area into contributing and noncontributing areas for hydrologic purposes. When the C/I ratio is used, the decision as to the relative sizes of the contributing and noncontributing areas does not have to be made.

In connection with Denison Reservoir, it seems desirable to present a brief discussion of the characteristics of the density current which passed through the outlets of Denison Dam.

In the middle of May, 1951, Denison Reservoir had a pool elevation about 5.4 ft lower than its normal pool elevation. It had about 2,480,000 ac ft of water in storage. At this time a large flow entered the lake from the Red River, which reached stages higher than any year since 1908. About four days after this inflow reached the upper end of the reservoir, about 50 mi above the dam, the outflow from the reservoir changed from clear to very muddy in color, even though the surface of the lake was clear for seven miles above the dam. This muddy underflow lasted about three days and was the first which has been observed to pass through the reservoir since it started operation in 1945. Most of the inflow originated in the western higher altitude portion of the Red River basin, where weather is usually cool in May. The Red River peak inflow was about 146,000 cfs. The reservoir was about 4.3 ft higher than normal when the muddy outflow stopped, and had about 3,360,000 ac ft of water in storage.

Table 2 shows the inflow, outflow, and measured suspended-sediment concentrations during the period of May 18-28, 1951. Sediment samples were collected only on the days for which a concentration is given in the table. The relatively small inflow on the Washita River arm of the reservoir is not shown, since it is believed the muddy underflow came entirely from the Red River.

Table 2--Data on the Red River

Date	Reservoir inflow		Outflow from reservoir	
	Mean daily flow at Gainesville gage	Suspended sediment concentration	Mean daily flow at Colbert gage	Suspended sediment concentration
May, 1951	cfs	pct by weight	cfs	pct by weight
18	1,090	. . .	3,490	Clear
19	35,800	1.35	3,320	Clear
20	84,500	0.85	5,580	Clear
21	138,000	0.49	11,300	Clear
22	117,000	. . .	22,500	Clear
23	64,300	0.45	32,400	0.39
24	34,000	0.47	38,600	0.86
25	22,100	. . .	38,100	Not determined
26	14,900	. . .	39,600	Clear
27	11,800	. . .	37,100	Clear
28	11,100	. . .	38,600	Clear

It may be estimated from Table 2 that during this flood not more than about 15 pct of the inflowing sediment passed through the reservoir. Since it might be ten years between such occurrences, this sort of a phenomenon may not have much significance as to the trap efficiency of the reservoir. However, it would probably be enough to remove the plotted point from the 100-pct line.

Grain-size analyses showed that of the sediment in the Red River inflow, about 40 pct of it was finer than four microns; about 40 pct of it was between four and 62.5 μ; and about 20 pct was coarser than 62.5 μ.

In the outflowing sediment it was found that about 54 pct of it was finer than four microns; about 44 pct of it was between four and 62.5 μ; and only about two per cent was coarser than 62.5 μ.

Observations in the six years prior to 1951 had not disclosed any muddy-bottom currents within 25 mi of the dam, so the May 1951 density current was a surprise, and its progress through the reservoir was not tested for sediment concentration, grain size, velocity, or temperature. However, colored movies of the outflow and certain portions of the reservoir were obtained from the air.

DISCUSSION OF

"RIVER MEANDERS AND VORTICITY THEOREM"
by LUNA B. LEOPOLD

[Trans., v. 34, pp. 955-958, 1953]

Robert R. Long (Department of Civil Engineering, The Johns Hopkins University, Baltimore, Md.)--In Leopold's paper conservation of circulation in a fluid circuit is assumed in the flow of water around regular windings of rivers and creeks. Before discussing the general results of the paper, I would like to mention the following specific points.

(1) Circulation C is described as a vector. It is actually a scalar.

(2) Vorticity ω is taken correctly as a vector, but is equated to the scalar $\delta C/\delta A$.

(3) The vorticity equation given in the paper

$$d\omega/dt = -\omega\left[(\partial/\partial x)(\rho v_x) + (\partial/\partial y)(\rho v_y) + (\partial/\partial z)(\rho v_z)\right] \quad \ldots\ldots\ldots\ldots (1)$$

is incorrect. It is, in fact, not even dimensionally homogeneous. It should be

$$d\vec{\omega}/dt = \vec{\omega} \cdot \nabla \vec{V} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

for an incompressible fluid if $\vec{\omega}$ is the vector vorticity (ξ, η, ζ) as defined in the paper.

(4) Aside from the incorrectness of the vorticity equation, if it is taken in the form of (1), it cannot be used for the later computations of the paper because the quantity in brackets is the total mass divergence and is zero. Thus $d\omega/dt$ and $-\omega(\mathrm{div}\ V)$, computed by the author in Figure 1 should be identically zero according to his equation.

(5) It is possible that the author intended to study the change of the vertical component of vorticity ζ since the equation

$$d\zeta/dt = -\zeta(\mathrm{div}_2\,\vec{V}) \qquad \mathrm{div}_2\,\vec{V} = \partial v_x/\partial x + \partial v_y/\partial y$$

is correct if terms such as $\xi\partial v_z/\partial x$, $\eta\partial v_z/\partial y$, are negligible in the stream, and if friction is neglected. This interpretation does not serve to clarify the result, however. Thus, the author's curves show a typical value of 10 $\sec^{-2}$ for $d\omega/dt$. Now this is closely given by $u\partial\omega/\omega s$ where u is a representative velocity of the stream and s is distance along the stream. Using the author's value of about two feet per second for u and approximating $\partial\omega/\partial s$ by $\omega/(\lambda/4)$, where λ is the wave length of 160 ft, we obtain $d\omega/dt = o(\omega/20) = o(10)$ or $\omega = o(200)$. But $\omega = o(\partial u/\partial n)$ where n is distance normal to the current, and this is of the order of 2/10, where ten feet is the half width of the stream. The author's graphs thus imply values of ω 1000 times greater than they should be.

More generally, the author states that if the largest velocity at the crossover is nearer the bank which was the outside or concave bank in the curve immediately upstream, conservation of circulation implies a downstream curve with curvature opposite to that of the upstream. This seems to be the main physical argument of the paper. I do not see why conservation of circulation would imply such a downstream bend. The water could just as easily keep moving in a straight line, with no change of shear, vorticity, or circulation.

Regarding the postulate that circulation is conserved, Leopold states that it is justified if the velocity-depth ratio is small. This parameter, being dimensional, could not be the pertinent parameter in this regard, since it will have, in general, different values for two river systems that are dynamically, kinematically, and geometrically similar in all respects. In the quoted paper by Wattendorf the ratio which is characteristic for this purpose is considered to be the non-dimensional ratio of width to depth. But Wattendorf finds rough experimental agreement with theoretical velocity distributions in curved flow, based on the assumption of constancy of circulation, when this ratio was 1:18, and his discussion indicates that he believes that it must be this small. In the creek studied by Leopold the ratio is about 300 times greater than this. Wattendorf further states that unless the ratio of width to depth is small (instead of large as in Leopold's case), the flow in bends is characterized by longitudinal vortices set up by boundary layer effects. Such a flow pattern carries vorticity generated at the boundaries into the body of the fluid, a condition that is incompatible with the assumption of constancy of circulation.

Luna B. Leopold (U. S. Geological Survey, Washington 25, D. C., Author's closure)--I acknowledge the correctness of Long's comments on the vorticity equation as written in my communication. Although my computations are in error, there is still something to be said for the physical reasoning. It seems inappropriate to attempt to defend that portion at this time, lacking a meaningful computation of the magnitude of the quantities involved.

REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

SCHNEIDER, H., and Others, Die Wassererschliessung (The Search for Water), Vulkan-Verlag Essen, 421 + xv pp. with 605 fig., cloth bound, 68.00 marks, 1952.

This is one of few books published on the hydrology of subterranean water. It comprises: (1) General hydrology considering the origin, accumulation, distribution, quality and quantity of subterranean waters (H. Schneider). (2) Methods of construction of wells and other water collecting structures, and the description of tools and equipment used in water-supply practice (C. Truelsen). (3) Search for water by the electric resistivity method (H. Thiele). (4) Technical information about well drills, pumps, pipes, etc., applied to water-supply practice.

It is a treatise of high scientific and technical standard and of the great value for modern water-supply practice. The importance of underground water to public economy all over the world is now well recognized, but the methods of the quantitative estimation of underground flow are still insufficiently studied in many respects.

This book summarizes the theoretical principles upon which the quantitative estimation of subterranean waters are based and provides very useful experimental data obtained chiefly by the author himself. It bears evidence of the high qualification, experience, and erudition of Schneider and his co-operators, and is based on the principles of the classical hydrology of subterranean waters carried out by Darcy and Dupuit and later developed mainly by German scientists.

Among numerous important problems treated in this book, the following can be mentioned:

Salinity of underground water--The study of subterranean water in Verden and in Herford (Westphalia) revealed the following relation between protracted supply and change in salinity.

Year	Location	Yearly supply	Chlorine content
		m^3	mg/ℓ
1925	Verden	150,000	35
1935	Verden	280,000	80
1947	Verden	750,000	325
1938	Herford	. . . .	90
1942	Herford	. . . .	190
1944	Herford	. . . .	300

This is one of few published results of the change in salinity of underground water under heavy pumping for a number of years, although this phenomenon is well known particularly in arid and semi-arid areas, where the deterioration in quality of water seriously affects, in many cases, the economic use of such water.

Schneider suggests that the relation between chlorine content in underground water and depth of a pumped well is well determined by the following

$$y = e^{x \log a}$$

where y is chlorine content, mg/ℓ; x is depth of well, meters; and a is coefficient depending on the type of the water-bearing bed.

The a-value can be computed when two y-values are found

$$\log a = (\log_e y_2 - \log_e y_1)/(x_2 - x_1)$$

and for a depth x_n where chlorine content is equal to y_n

$$x_n = [(x_2 - x_1) \log_e y_n]/(\log_e y_2 - \log_e y_1)$$

Coefficient of permeability--Schneider states that the variation in the k-value (the coefficient of permeability) of the water-bearing bed takes place with the intensity of the pumping of a well. The following relation between k and i (the hydraulic gradient) was found: (1) In the first zone located immediately to the well (Zunker's critical gradient), k decreases with the increase of i. (2) In the second zone located within hydraulic gradients of two to 12 pct, k slowly increases with the increase of i (in fine-grained sand); this is actually a zone where k can be considered as a constant. (3) In the third zone it is found where i is from 0.3 to two per cent, a strong change of the k-value is typical for this zone. (4) In the fourth zone in which $i < 0.3$ pct; k decreases here with the decrease of i.

This relation between k and i leads to a very important practical application of the problem particularly in the drainage and artificial replenishment (recharge) of underground waters, where the optimum hydraulic gradient can be created.

Recharge of a well--Although the recharge of underground water has been known since 1897 (Richert, Sweden) there are still many unsolved problems in water recharge practice. Schneider suggests the following equation for the computation of the amount of water (S) recharged in a well with unconfined water

$$S = [\pi k\ (2H\ z + z^2)/\log_e (R/r)]\ \mathrm{m^3/sec}$$

where k is coefficient of permeability, m/sec; H is thickness of the water-bearing bed, meters; z is thickness of the column of water in recharged well above the water table, meters; R is radius of influence of the recharged cone of depression, meters; and r is radius of recharged well, meters.

Numerous graphs show that z depends on the magnitude of S and at first it decreases quickly and after then the curve acquires an asymptotic shape. The relation between z, S, and r when H and k are constant shows that $r = 0.5$ m is the optimum radius of a recharged well and Schneider suggests that it is rather advisable to put down more recharged wells than increase their radius.

Pumped well--Truelsen recommends the following avenue for determining of the velocity with which underground water flows into a well: For a given value of k, the greatest value of i is determined from Sichardt's equation

$$i_o = 1/15 \sqrt{k}$$

and the maximum velocity

$$V_o = ki_o$$

Since (after Hazen) $k = 0.0116\ d_e^2$ or $k = d_e^2/86.2$, where d_e is the "effective" diameter of particles

$$V_o = k/15 \sqrt{k} = Vk/15 = \sqrt{d_e^2/86.2}/15 \approx d_e/140$$

Schneider considers the problem of the yield capacity of a well in relation to the size of a pumped well and critically analyzes the problem of the k-value and particularly Smreker's exponent which was found to be less than one instead of one to two as it was believed.

Electric-resistivity method--Thiele's paper is considered as one of the most significant publications on the subject. No similar work is known to have been published previously in any other country. It covers a whole field of the electric-resistivity method in the search for water, including the physical - mathematical principles and apparatus, the natural properties of soil and subsoil, electrochemical properties of water, and other factors. These problems are treated using the modern scientific concepts, and their application is of a great interest and practical value. Numerous tables, graphs, and maps supplement the subject matter.

A general estimation of the book--It would be wrong to imply that this book has no defects and that it solves all the problems of modern underground water-supply practice. There are some insufficiently clear passages, formulations, and even wrong statements; and some graphs and figures are, unfortunately, illegible. There are also a number of important underground-water problems which are not considered in this book. Among them may be mentioned the hydrology of the interstitial rocks, the yield capacity of wells which do not pass through the water-bearing bed, some aspect of geochemistry of subterranean water. But it should be borne in mind that many problems of hydrogeology are not yet solved and it is impossible to compile in one volume the details of all the problems. On the whole, this book can be considered as a valuable contribution to the study and utilization of subterranean water.

I. Ch.

ROE, HARRY BURGESS, and QUINCY CLAUDE AYRES, Engineering for Agricultural Drainage, McGraw-Hill, 600 pp., 1954, $7.50.

The benefits of drainage in all countries are well presented in the text. An interesting review of progress is presented. Of special importance is the statement of popular fallacies concerning drainage. It is vital to agricultural progress everywhere that people understand fully the values of drainage. Drainage does not destroy the habitat of wild life; nor does it lower regional groundwater tables permanently and thus menace the growth of trees or obliterate lakes and ponds of value to man.

The authors' outline of soils in relation to drainage is excellent and their stressing the vital effect of soil-moisture control is important to drainage progress.

A comprehensive resumé is presented concerning the engineering procedures in design, construction, and maintenance of open ditches for agricultural drainage. The discussion of design, construction depths, and spacing of tile for under-drainage is new and up to date. Also a very fine resumé of drain tile, kinds, classes, and standards is presented.

One of the most important aspects of the text with respect to the 17 western states in the United States and to arid region areas in many countries is the chapter on the drainage of irrigated lands. Although brief and condensed, it contains vital factors of importance to reclamation of waterlogged lands in the West, leaching of excess soluble salts and of the necessity of drainage to perpetuate irrigation agriculture on a profitable and sound basis.

(Figure 41 shows a map of rainfall in the United States that was published about 1906. More up-to-date maps are readily available from the U. S. Weather Bureau. The current-meter apparatus pictured on page 125 has been obsolete for more than 30 years.--Ed.)

O. W. ISRAELSEN

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NOTES AND PERSONALIA

NOTES

Conference on Atmospheric Electricity--The American Geophysical Union held a Conference on Atmospheric Electricity at Portsmouth, New Hampshire, May 19-21, 1954. This Conference was arranged under contract with the Air Force Cambridge Research Center and had for its purpose the appraising of the present situation with regard to research in atmospheric electricity and to chart possible pathways for the future. About 60 were in attendance including 11 distinguished scientists who were brought from overseas especially to participate in the Conference. A report including the papers and discussions of the Conference is in preparation.

Dedication of Oceanographic Laboratory and Oceanographic Convocation at Woods Hole--The new Laboratory of Oceanography, built by the Office of Naval Research under contract with the Woods Hole Oceanographic Institution, was dedicated on June 21. This was followed by a three-day Convocation on Oceanography at which leading oceanographers from all over the world were the speakers. About 300 were in attendance. The Convocation was sponsored jointly by the National Academy of Sciences-National Research Council, Office of Naval Research, the Marine Biological Laboratory, Woods Hole Oceanographic Institution, and the Fish and Wildlife Service.

Survey of research and development activities in the United States--The National Science Foundation has announced that, in connection with its broad survey of science in the United States, four studies on research development in the United States are under way. These include: (1) a survey of industrial research and development being conducted by the Bureau of Labor Statistics in cooperation with the National Science Foundation; (2) a survey of research by state governments undertaken in two parts by the Bureau of Census and by the Institute for Research in Social Science, University of North Carolina; (3) a survey of research by trade associations and similar associations to be conducted by the Battelle Memorial Institute; and (4) a survey of research at non-profit institutes and commercial laboratories being conducted by the Maxwell Research Center of Syracuse University. It is anticipated that the surveys will be completed by the end of 1955.

Newsletter of the American Geological Institute--It is the plan to send this newsletter, starting with the September 1954 issue, to everyone whose name and address appear in the Earth Sciences Section of the National Register of Scientific and Technical Personnel. The questionnaires relating to this Register were sent out by the American Geophysical Union last November, and those who have not forwarded these to the American Geological Institute should do so without further delay. The newsletter has adopted a new format, being an eight-page, three-column leaflet, and contains many items of interest in all fields of geophysics.

Grants of the National Science Foundation--The National Science Foundation has recently announced the awarding of grants totaling approximately $1,359,000 for research in the natural sciences and related work. Among the grants are those to G. Tunell of the University of California to study the geochemistry of mercury ores; to D. B. Ericson of Lamont Geological Observatory for lithological and micropaleontological investigation of Atlantic Ocean sediment cores; to P. B. Sears of Oberlin College to continue history of vegetation, climate, and sediments extending into the Pleistocene; to B. F. Howell, Jr., of Pennsylvania State University for study of the formation of seismic pulses; to S. F. Singer of the University of Maryland for study of the ultrahigh-energy cosmic rays; to G. L. Clarke of Woods Hole Oceanographic Institution for study of the penetration of light into the sea and its effect on aquatic organisms; and to the U. S. National Committee for the International Geophysical Year for its preliminary work in connection with this activity.

Glaciological research in Canada and Alaska--A team from California Institute of Technology led by Robert P. Sharp, Chairman of the Division of Geological Sciences, is engaged in the scientific study of the Saskatchewan Glacier in the Canadian Rockies and the Malaspina Glacier in Alaska. This summer's chief project is to establish a bore hole approximately 1500 ft deep near the upper reach of the Saskatchewan Glacier using the hotpoint method. The work is being sponsored by the Office of Naval Research and has the aid of the U. S. Coast Guard and the Civil Aeronautics Authority.

Directory of Geologists and Exploration Geophysicists--The American Geological Institute has issued this Directory, containing about 20,000 names. Copies may be secured from the Institute at 2101 Constitution Avenue, Washington 25, D. C., for $2.50.

Awards of the Gravity Research Foundation--The Gravity Research Foundation, New Boston, New Hampshire, is offering, for the sixth year, five awards for essays on gravity. The awards will be made on December 1, based on essays 1500 words in length, and range from $1000 to $100. The essays must be submitted before October 15. Further details may be secured by writing to the Foundation.

Manual on Underground Hydrology--A new committee has been appointed by the American Society of Civil Engineers to prepare this Manual. The chairman of the committee is Harvey O. Banks of Sacramento. Dean C. Muckel of Pomona, California, and Frederick L. Hotes of the University of California are among those included on the committee.

New geophysical curriculum at Georgia Institute of Technology--Georgia Institute of Technology recently established an undergraduate curriculum leading to a Bachelor of Science in Physics, Geophysics optional. The requirements are about those set forth by the Geophysical Education Committee of the American Institute of Mining and Metallurgical Engineers in 1943, including a major in physics and a minor in mathematics and geology with additional work in chemistry and engineering, and bears especially on the hard-rock aspects of geophysics.

Meeting of the Advisory Committee on Arid Zone Research--The Seventh Session of the Advisory Committee on Arid Zone Research met in Paris, May 4-7, 1954. A brief report on the meeting is contained in Science, volume 120, page 15, July 2, 1954. Gilbert F. White, President of Haverford College, is the representative from the United States for this Committee.

Work on the Coral Atoll Project--The five-year program on this Project is continuing, supported by funds from the Office of Naval Research and under the guidance of the Pacific Science Board. At the present time, a team is at work on the islands gathering data relative to the study of environmental factors in relation to life on the atolls.

Waterways Experiment Station observes 25th anniversary--The Waterways Experiment Station celebrated its 25th birthday by an open house, June 18-20, 1954. Several thousand visitors, including some of the country's leading scientists and engineers, inspected the Station's facilities, both at Vicksburg and at Jackson.

Third International Congress for Alpine Meteorology--This Congress was held in Davos, Switzerland, April 12-14, and was attended by representatives and delegates from various countries including the United States. Arthur W. Johnson, Meteorological Attaché at Geneva, Switzerland, and Henri Bader, Chief Scientist of the Snow, Ice, and Permafrost Research Establishment, were among those who attended. About 150 were in attendance from ten countries, most of them from Austria, Germany, and Switzerland.

Golden Jubilee of the Alibag Observatory in Bombay--Plans are under way for the celebration of the 50th anniversary of the Alibag (Bombay) Magnetic Observatory. It is planned to publish a special number of the Indian Journal of Meteorology and Geophysics in honor of the occasion.

ECAFE Conference in Tokyo--This Conference was held May 17-22 in Tokyo and was attended by about 110 delegates and observers from 18 countries. This was a six-day regional technical conference on the development of water resources and was organized by the United Nations Economic Commission for Asia. Representatives of various other U. N. agencies were also in attendance.

PERSONALIA

W. Douglas Baines of the Fraser River Model of the University of British Columbia has been named the recipient of the J. C. Stevens Award of the American Society of Civil Engineers for his paper entitled Application to an Hydraulic Problem.

Willard Bascom of Scripps Institution of Oceanography is on leave serving as Executive Director of the Advisory Committee on Civil Defense of the National Research Council.

Dirk Brouwer, Director of the Yale University Observatory, participated in the international astronomical meeting held in connection with the dedication of Pulkovo Observatory near Leningrad. He was designated by the National Academy of Sciences and the National Science Foundation.

Jule G. Charney, Institute for Advanced Study, presented a series of six lectures on the theme Scale and Stability in Planetary Fluid Motions at Woods Hole Oceanographic Institution as their Associates Lecturer for 1954.

H. P. Coster has resigned his position with the Seismograph Service Corporation to accept a position as Geophysicist for the Shell Oil Co. in Houston.

John S. Cotton, Consulting Engineer, has moved his headquarters from San Anselmo, California, to Kentfield, California.

Albert E. Cummings, Director of Research for the Raymond Concrete Pile Co., has been appointed a member of the Advisory Committee of the Research Division, College of Engineering, New York University.

Lloyd Espenschied of Bell Telephone Laboratories has retired after 44 years of service with the Bell Telephone System. He has been granted more than a hundred patents for his inventions and with Herman A. Affel is the inventor of the coaxial cable system.

Rhodes W. Fairbridge, who has been Visiting Professor in the Geology Department at the University of Illinois, is spending the summer at Scripps Institution of Oceanography working on material of the Capricorn Expedition. He will return to the University of Western Australia this fall.

John W. Gabelman has resigned as Geologist with the American Smelting and Refining Co. with headquarters in Salt Lake City and has accepted a position as District Geologist with the Atomic Energy Commission with headquarters in Grand Junction, Colorado. His work will be concerned with the Colorado Plateau.

Robert M. Garrels has left his work with the U. S. Geological Survey to accept appointment as Associate Professor of Geology at Harvard University.

H. R. Gault is returning to Lehigh University as Professor of Geology after devoting a year of leave to work as Executive Secretary of the Division of Earth Sciences, National Research Council.

Beno Gutenberg, Professor of Geophysics and Director of the Seismological Laboratory of the California Institute of Technology, has been elected a Foreign Member of the Geological Society of London.

Vaughn E. Hansen of Utah State Agricultural College has been named the recipient of the Collingwood Prize for Juniors of the American Society of Civil Engineers for his paper entitled Unconfined Ground-Water Flow to Multiple Wells.

William T. Holser has left his duties as Assistant Professor of Geology at Cornell University and has accepted the position as Principal Geochemist at Battelle Memorial Institute. He will initiate a new program of experimental mineralogy to serve industry and the government.

Charles R. Hursh has retired as Chief of the Watershed Management Research Division of the Southeastern Forest Experiment Station at Asheville, North Carolina. He was in charge of research on the relation of climate, soil, and forest vegetation to stream flow at the Experiment Station for 30 years.

Hamilton McKee Johnson, formerly associated with the Schlumberger Well Surveying Corp. and the Seismograph Service Corp., has received the Ph.D. degree in geology and geophysics from the University of Oklahoma. He will return to active field work with the Texas Petroleum Co. with headquarters in Caracas, Venezuela.

Hisashi Kuno of Tokyo University has been awarded the Academy Prize for his work entitled Petrological Studies on Pyroxenes. The award was made on May 12 by the Japan Academy in the presence of the Emperor.

Joseph S. Pluta has resigned his position with the Century Geophysical Corp. and has accepted a position as Geophysicist for the Honolulu Oil Corp. with headquarters in Midland, Texas.

Louis O. Quam has been named Vice President of the Association of American Geographers.

Robert V. Ruhe, Research Geologist in the Division of Soil Survey of the U. S. Department of Agriculture, collaborating with the Iowa Agricultural Experiment Station, has received a grant-in-aid from Wenner-Gren Foundation for Anthropological Research to conduct geopedological research in the Belgian Congo and other parts of Africa during the last part of 1954.

Vincent J. Schaefer has left his work with the General Electric Research Laboratory and is now Director of Research of the Munitalp Foundation.

Robert B. Sosman, Professor of Ceramics at Rutgers University, has been awarded an honorary doctorate by the University of Toledo.

Charles E. Stearns, Assistant Professor of Geology at Harvard University, will become Dean of the School of Liberal Arts of Tufts College in September.

Harold A. Thomas, Jr., of Harvard University has been named co-winner of the Rudolph Hering Medal of the American Society of Civil Engineers, for the paper of which he was co-author (with Ralph S. Archibald) entitled Longitudinal Mixing Measured by Radioactive Tracers.

M. A. Tuve of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, has been named Chairman of the National Science Foundation's Advisory Panel for Radio Astronomy.

Harold K. Barrows, Consulting Engineer, and Professor Emeritus of Hydraulic Engineering, Massachusetts Institute of Technology, died March 15, 1954, at the age of 80. He was born at Melrose, Massachusetts. He took his baccalaureate degree from MIT in Civil Engineering in 1895. After terms of service with the City Engineer of Newton, Massachusetts, the Metropolitan Water Board of Boston, the University of Vermont, and the U. S. Geological Survey, he established his own consulting firm in 1907, and began his educational work at MIT in 1909. He retired from his work at MIT in 1941, but continued actively his work as consulting engineer until a short time before his death. His text and reference book, Waterpower Engineering, has long been considered a classic. He had been a member of AGU since 1932.

Frederic W. Darling, Mathematician with the U. S. Coast and Geodetic Survey from 1919 until his retirement in 1949, died April 21, 1954, at the age of 75. He was born in Buffalo, New York. He took his baccalaureate degree from Cornell in 1903, pursuing further studies in the succeeding year and in 1913-1914. He studied at the University of Michigan in 1904 and 1905. His earlier professional years were spent as a high school teacher in Montana, Ohio, and New York, work with the Bureau of Forestry in the Philippines, and in diverse activities. His interests included isostasy and the figure of the Earth, geodetic astronomy, and deflection of the vertical. He had been a member of AGU since 1934.

Antoni Bolestaw Dobrowolski, student of cryology, and author of various works on snow, ice, and clouds (including his Natural History of Ice in 1923), died in Warsaw, Poland, April 27, 1954.

Albert W. Giles, Professor of Geology at the University of Arkansas, died May 15, 1954, at Van Buren, Arkansas. He was born at Watkins, New York. He took his baccalaureate degree from the University of Rochester in 1909, and his master's degree from the same school in 1910. In 1922 he took his doctorate at the University of Chicago. The earlier years of his professional career were spent as a teacher of geology at Allegheny College, Kansas Wesleyan, University of Chicago, and the University of Virginia. He began his work at the University of Arkansas in 1926. His studies included the stratigraphy of Arkansas and Virginia, the structure of the Appalachians, and paleo-climatology. He had been a member of AGU since 1945.

Alfred C. Hawkins, consulting geologist and Professor of Geology at Brooklyn Polytechnic Institute, died March 30, 1954, at the age of 66. He was born at Sewaren, New Jersey. He took his baccalaureate degree at Columbia in 1909, his master's degree at Princeton in 1912, and his doctorate at Brown in 1916. He was an assistant in geology at Princeton while studying for his master's degree and an instructor at Brown while working on his doctorate. Subsequently, he engaged in work with the du Pont Co., taught at the University of Rochester and Rutgers University, and had been doing consulting geological work since 1935. His studies included the areal geology of Rhode Island and the structural geology of New Jersey and New York. He had been a member of AGU since 1948.

André Raymond Marie Nizery, Chief Engineer and Director of Research, Electricité de France, working on hydrological problems, died February 27, 1954, at the age of 46. He was born in Le Havre. He studied at Ecole Polytechnique in Paris and Ecole Nationale des Ponts et Chaussées. Subsequently he was engaged in work at Port of Dakar, in the office for scientific research relating to French colonies in Paris, and as Director General of the Société Hydrotechnique de France. He entered the services of Electricité de France in 1946. He was a recipient of the Légion d'Honneur and the Croix de Guerre. He had been a member of AGU since 1951.

Paul T. Seashore, formerly Vice President of the Louisiana Land and Exploration Co. in New Orleans, died at his home at Carmel Valley, California, on April 11, 1954. He was born at Grand Forks, North Dakota, July 5, 1898. He studied in the University of Texas, subsequently working as a Hydrographer for the U. S. Department of Agriculture and the Texas Board of Water Engineers. He then went to petroleum engineering and subsurface geological work, which took him into the service of the Louisiana Land and Exploration Co. He had been a member of AGU since 1945.

Frank Wenner, consulting physicist and geophysicist, retired, died in Washington, D. C., February 7, 1954, at the age of 81. He was born at Garrison, Iowa. He took his baccalaureate degree from Knox College in 1899 and his doctorate from the University of Pennsylvania in 1909. He was awarded an honorary Doctor of Science degree by the University of Pennsylvania in 1942. His early professional years were devoted to teaching at Knox College, University of Wisconsin, Iowa State College, and the University of Pennsylvania. In 1907 he entered the service of the Bureau of Standards from which he retired in 1943. Since that time, he had been active as a consulting geophysicist for various organizations and served the National Military Establishment in various capacities. He was the recipient of the Wetheral Medal of Franklin Institute and served as the President of the Section of Seismology of AGU from 1932 to 1935. His studies included the development of galvanometers for the measurement of inductance and resistance, seismometers, the study of Earth resistivity, and the measurement of time. He had been a member of AGU since 1929.

Paul C. Whitney, Captain, U. S. Coast and Geodetic Survey, retired, died in Leonard, North Dakota, June 19, 1954, at the age of 71. He was born in Washington, D. C., and studied at George Washington University. He entered on duty with the Coast and Geodetic Survey in 1902 and retired in 1946. During his long career with the Coast and Geodetic Survey he served in various capacities and in various parts of the world. Just prior to his retirement, he was Chief of the Division of Tides and Currents for 14 years. He served the American Geophysical Union in various capacities, notably as Chairman of the Committee on Membership and as Secretary and President of the Section of Oceanography. He had been a member of AGU since 1930.

Transactions, American Geophysical Union Volume 35, Number 4 August 1954

MINUTES OF EXECUTIVE COMMITTEE MEETING, AMERICAN GEOPHYSICAL UNION

First Session, May 2, 1954

The meeting was called to order at 14h 30m in the Board Room of the National Research Council - National Academy of Sciences Building, 2101 Constitution Avenue, Washington, D. C., by President James B. Macelwane.

Present--Thirty-three persons were present, namely: L. H. Adams, John Adkins, L. R. Alldredge, Wallace W. Atwood, Jr., K. Hilding Beij, L. V.Berkner, Francis Birch, Walter H. Bucher, James J. Capello, Felix Chayes, Phil E. Church, Frank L. Culley, E. A. Eckhardt, William F. Foshag, Harry H. Hess, William E. Hiatt, Albert J. Hoskinson, Woodrow C. Jacobs, J. W. Joyce, Joseph Kaplan, Walter D. Lambert, Gordon G. Lill, James B. Macelwane, John Putnam Marble, Walter H. Munk, James A. Peoples, Jr., Donald W. Pritchard, William W. Rubey, Waldo E. Smith, Harlan T. Stetson, Victor Vacquier, Harold G. Wilm, and George P. Woollard. The following were excused: Robert Balk, Hugo Benioff, J. A. B. Bjerknes, Harry F. Blaney, Perry Byerly, Maurice Ewing, Jno. A. Fleming, R. H. Fleming, Beno Gutenberg, Ross R. Heinrich, Benjamin Holzman, H. R. Joesting, C. O'D. Iselin, E. S. Larsen, Jr., Ray K. Linsley, Gordon C. Macdonald, Jerome Namias, William A. Noyes, Jr., Brian O'Brien, A. C. Redfield, A. Nelson Sayre, M. O. Schmidt, L. B. Slichter, F. J. Veihmeyer, J. Verhoogen, E. H. Vestine, Paul A. Weiss, and James T. Wilson.

Approval of Minutes--The minutes of the Executive Committee meeting of November 28, 1953, published in the April, 1954, issue of the Transactions, were approved.

General Secretary's Report

This Report covers the various official activities of your General Secretary since the date of his previous Report - November 28, 1953. It is essentially a factual report of matters that have arisen and of action that has been taken. Certain recommendations are added at the end, for consideration at this meeting, and certain other matters for action have been included in the agenda. Needless to say, other matters will arise during the course of our discussions.

As a matter of convenience, this Report has been divided into four sections: (1) Publications, (2) activities of the Union in its own domain, (3) activities of the Union as the American Committee of the International Union of Geodesy and Geophysics, and as the Committee on Geophysics of the National Research Council, and (4) sundry matters.

Publications

Three numbers of the Transactions have been published. The December, 1953, number contained 156 pages; the February, 1954, number, 192 pages, including the History of the Union by Honorary President J. A. Fleming and the Symposium on the Earth's Interior; the April, 1954, number, 196 pages, including 36 pages of the program for the Thirty-Fifth Annual Meeting. Since 1950 we have paginated the program in the Transactions, but because of many claims of loss of the separate program, we have this year, as an additional service to our members, bound it in at the end of the April number.

The backlog of unpublished manuscripts, which have received or are receiving editorial consideration, continues uncomfortably high, about 100 papers, or nearly a year's normal publication. Our present financial position does not permit increasing the number of printed pages by any appreciable amount. We have made application for a grant from the National Science Foundation for $7900 to enable us to increase our issues from about 160 to about 200 pages for about 18 months. Should this grant be given to us, it will only be a stopgap. We are being urged to improve our format, which will cost money, and we have an opportunity to add several excellent papers on nuclear geophysics and geochemistry if we can ensure reasonably prompt publication.

General activities

Membership--This continues to grow slowly. Incidentally, your General Secretary has seen recently figures from some other scientific groups which show very close to a decline, so we are pretty well off. Figures are

Membership as of November 25, 1953	5013	
New members, November 25, 1953 - April 25, 1954, including 25 applications now being processed	141	
Reactivated	1	5155
Resigned (adjusted figure)	93	
Dropped (adjusted figure)	0	
Inactive	7	
Deceased	15	115
Membership as of May 1, 1954		5040

The following deaths have been reported since our last meeting: Frank B. Littell, November 28, 1951; Robert F. Ewald, July 17, 1953; Verle L. Austin, July 27, 1953; Kent K. Kimball, August 9, 1953; Earle W. Johnson, August 11, 1953; John J. O'Neill, August 30, 1953; L. A. Scholl, Jr., September 22, 1953; Robert Tsai-Hsing Chen, November 3, 1953; Leonard J. Neuman, December 18, 1953; Robert A. Millikan, December 19, 1953; Ralph E. Digman, December 20, 1953; Nicholas H. Heck, December 21, 1953; LeRoy K. Sherman, January 5, 1954; Frank Wenner, February 7, 1954; A. Nizery, February 27, 1954.

The latest information in the office shows that 144 members have not paid dues since 1952, and three more have paid dues for 1952 in part only. It is required that these be reported by your General Secretary with the recommendation that they be dropped from membership. As usual, we make the further recommendation that the office be instructed to make an additional effort to get them to return to good standing. Last year we had at this time about 190 delinquents on our rolls. The "last appeal" reduced the number dropped to less than 150. Many paid up and are now in good standing; some paid for 1951 and resigned in good standing as of the end of that year.

Finances--These appear to be in good shape. The audited financial statement for the year ending June 30, 1953 was printed in the April, 1954, *Transactions*, pages 343-345.

It should be remembered in considering what follows that at this time of year we have received nearly all of our income, but have paid out less than half of our expenses for the calendar year. Our cash balance April 1, 1954 was $21,742, compared with $20,919 a year ago, $24,523 in 1952, $19,267 in 1951, $17,163 in 1950, and $15,653 in 1949. Also the Permanent and Emergency Funds are at all-time highs, the former totaling $10,368 and the latter $1,043. We feel that it is better to keep our funds fluid at 3 to 3 1/2 pct and not to set up a securities purchase program under professional or committee advice, at some higher cost and risk, particularly considering the modest amount of our funds and the uncertainty of future arrangements. In addition, we have recently set up a new account in the Liberty Building Association to care for gifts for an Award in Terrestrial Magnetism and Electricity. These now total $210 and there are pledges for somewhat over $3000 more.

Budget--Receipts are running about $1000 over those anticipated in the budget. Expenditures are running slightly higher than budgeted, but not as much so as receipts, so we anticipate a somewhat greater margin than was allowed for a year ago. The chief items of excess expenditure are: Printing *Transactions*, increase of edition from 5600 to 5900, and larger issues, about $900; preparation of *Transactions*, about $200; and salary items, $200. There are some items that run slightly less than budgeted, which partly compensate. (Authority for needed adjustments was granted.)

Office staff--This consists of J. J. Capello, Mrs. Nancy Ing, Mrs. Susan Cha, and a replacement for Miss Irene Danthine (who has just left us for a position in the Belgian Embassy, she being a Belgian national), all under the direction of Executive Secretary Waldo E. Smith.

Quarters--The Carnegie Institution of Washington has generously granted us permission to retain our present office space in their building at 1530 P Street, N.W., Washington 5, D. C., without charge, through January, 1955.

Committees--The following Committees were discharged with thanks at the November meeting of this Committee, since their Chairmen felt their work was completed: Tsunamis, Geophysical and Geological Study of Ocean Basins, Surveys and Maps. (The Budget Committee and the Special Committee on Relations with the National Research Council will report at this meeting, with routine reports from others. The May meeting of the Editorial and Publication Committee will be held in the Conference Room, Carnegie Institution of Washington, on Thursday, May 6, 1954. We hope for a full attendance.)

American Geological Institute--Authors' abstracts of papers published in our Transactions are regularly published in Geological Abstracts, which now appears in a more attractive format, being published for the Institute by the Geological Society of America. A revised Constitution and By-Laws for the Institute has been received and referred to our Committee on Statutes and By-Laws, which recommended appropriate action. Action, as a Member Organization of the Institute, upon the request of the American Association of Geology Teachers to receive the same status is needed. (This was approved subsequently.)

New committees--On request of members of the Northwest Pacific Region, an *ad hoc* committee for the organization of a Northwest Regional Branch has been appointed.

Non-budgetary activities--A contract in the amount of $20,000 has been signed between the National Academy of Sciences - National Research Council and the U. S. Air Force, with the financial assistance of the U. S. Navy, the Union acting as agent for the NAS-NRC for a closed Conference on Atmospheric Electricity to be held at Portsmouth, N. H., May 19-21, 1954. Final arrangements are virtually complete.

A contract between NAS-NRC and the Department of the Interior for the preparation and publication of the Bibliography of Hydrology and Sedimentation for 1951-1954 has been drawn up, and will shortly be signed. Here again the Union acts as the agent of NAS-NRC. An adequate supply of copies will be furnished the Union, largely for transmission to the International Association of Hydrology.

Neither of these items is involved in the budget of the Union, and both will be carried out without cost to the Union.

International activities

Tenth General Assembly of the International Union of Geodesy and Geophysics--Our final list of suggested delegates (nine plus four alternates) to receive credentials from the State Department, and 27 more plus alternates to receive credentials from the NAS-NRC has been made and approved by appropriate authorities. Preliminary programs of the various Associations have been received in our office, but no final arrangements appear to have been made by the Italian organizing and executive committees. Partial travel grants for some of our delegation have been made by the National Science Foundation.

The Third International Conference on Alpine Meteorology--This was held in Davos, Switzerland, on April 12-14, 1954. The Union was represented by Arthur W. Johnson, U. S. Meteorological Attaché at Geneva. Henri Bader of the Snow, Ice, and Permafrost Research Establishment, a member of the Union, also was present.

International Geophysical Year--The Committee on IGY will meet in Rome immediately following the meeting of the IUGG. Joseph Kaplan, the Chairman of the U. S. National Committee, has attended our meeting. (He requested suitable support from the appropriate Committees and Sections of the Union for the related activities of his group.) Representatives of the Union have attended, by invitation, recent preliminary meetings of the U. S. National Committee and affiliated bodies in Washington.

Other international matters--There will be many international meetings in Europe late this summer and early this fall. Among them are the Congres International de Chronometrie, URSI, and IUTAM. Members of the Union will attend several of these, but we will not appoint official delegates.

National Research Council activities

The Special Committee of Berkner (Chairman), Bucher, and Macelwane to consider the relations of the Union with the NRC in various matters has been engaged in conferences with appropriate officials of NRC and reported at this meeting.

We have recently been asked by the Division of Physical Sciences to appoint a representative on it, to serve the same purposes in this connection as does our representative on the Division of Earth Sciences. Similar requests may be received from other Divisions.

In connection with various expected changes in our relationship to the NRC, we expect the need to make changes in our Statutes and By-Laws. As the matter is at present in a state of flux, we shall refer questions to the Committee on Statutes and By-Laws in due course for later report.

Sundry matters

The Arid Zone Conference, held on Saturday, April 24, 1954, was attended by the Executive Secretary as our representative.

We have been asked to appoint a representative to the Inauguration of the new President of Texas A and M College. We wait word from one of our prominent members in the area as to whether he can so act.

The Micro-Card Foundation has been permitted to micro-card our Transactions through 1953. Some of the issues of that year are already out of print, and the service is appreciated by inquirers. The recent increase in our press-run for 1954 will, we hope, avoid this embarrassment in the future.

The General Secretary and Executive Secretary attended April 29, 1954, a National Science Foundation Conference on Scientific Personnel Information in the Earth Sciences.

In concluding this report, I take the opportunity to express my heartiest thanks to our efficient, effective, loyal, and all-too-modest Executive Secretary, Waldo E. Smith. I would have been completely lost without his cheerful and invaluable assistance.

John Putnam Marble, General Secretary

Action on the General Secretary's report--The report was accepted.

Action on recommendations of the General Secretary--The recommendations of the General Secretary with respect to members who had not paid dues from 1952 to 1954 were approved, namely, that one more attempt be made to return them to active membership, following which those who do not respond will be dropped.

Comments by the President--The President reported that he feels the Union is in a healthy condition excepting for the backlog that we are accumulating for publication. He expressed the thought that we should at all times strive for prompt publication, and if we have any substantial backlog we tend to defeat that purpose. He noted that an application has been filed with the National Science Foundation for a grant to help us to get caught up on our present backlog, and in the interim plans must be developed either in the way of increasing our membership and subscribers or increasing our dues rates in order that the backlog will not accumulate again. He asked for suggestions with regard to steps that we should take for a long-range program. It was mentioned that with a membership of 6000 we would be able to increase the size of our Transactions to eliminate the accumulation of our backlog again without an increase in dues, but if our membership stays substantially as it is a dues increase appears to be the prime method for overcoming the tendency to accumulate a backlog. It was noted that while the Editorial and Publication Committee is being increasingly critical with respect to papers received, there is perhaps still opportunity to insist that authors eliminate a tendency towards wordiness and that the Committee should make such a requirement for the publication of papers, at the same time being more critical of each paper as a whole. It was noted that if we could increase our membership to 7000, we could not only increase the size of the Transactions but at the same time probably print our Transactions with justified right-hand margin which was deemed highly desirable and important by about one-third of those in attendance at the Executive Committee meeting.

International matters

Tenth General Assembly of the International Union of Geodesy and Geophysics--It was noted that this Assembly is to be held in Rome, Italy, September 14-25, 1954, and that while the total list of scientists and technologists from the United States who plan to attend is approaching 100, about 40 have been tentatively named by the National Research Council as official delegates of the Council to the Assembly. Of these, nine with four alternates have been nominated by the Academy-

Council as voting delegates of the State Department. Although no further word has come from the Italian Organizing Committee since the formal invitation which arrived last fall, word from General Secretary Laclavere indicates that plans are progressing rapidly in Italy and that the Associations' and Union's plans for the programs are likewise nearing completion. Director Atwood of the Office of International Relations noted that the dues question would come up at the meeting in Rome and that the United States position favors an increase in dues, but that this should be done on the unit basis. He noted that on May 24 there is to be a meeting of the Committee on International Scientific Unions composed of the Chairmen of each of the National Committees and that the voting delegates to meetings this summer are also to be invited in order to go over matters of procedures and policies. Also, Director Atwood noted that the matter of federation of the Unions of the International Council of Scientific Unions into groups is coming up for a vote, although there has been much opposition to the federation idea as it tends to establish one more level in the set-up that is already quite complex.

International Geophysical Year--Joseph Kaplan, Chairman of the United States National Committee for the International Geophysical Year, outlined briefly the plans that are developing for research work on the part of the United States, and L. V. Berkner, Vice Chairman of the ICSU Committee on the International Geophysical Year, offered further word on the overall plan of cooperation. (For details with regard to current plans, see Science of April 9, 1954, v. 119, p. 457.) He noted that there is to be a meeting of the ICSU Committee on the International Polar Year in Rome immediately following the meeting of the International Union of Geodesy and Geophysics, and it is hoped that at this meeting the various national programs may be integrated into a single international program or plan which can be circulated in 1955.

Reports of Standing Committees

Meetings--Chairman Adkins reported that the Thirty-Sixth Annual Meeting will be held May 2-4, 1955, in the week immediately following the meeting of the National Academy of Sciences. The meeting of the USA National Committee of URSI will be held May 3-6 next year, tending somewhat to conflict with our meeting, but by knowing this well in advance it is felt that the meetings can be coordinated. Chairman Adkins noted also that the Pacific Southwest Regional Meeting will be held in California in late January or early February, 1955, and that the Regional Committee had indicated it would prefer not to join formally with the AAAS meeting to be held in the Berkeley-San Francisco area in late December, 1954.

Statutes and By-Laws--Chairman Beij presented the report shown in Appendix 1. This was extensively discussed mainly with respect to the comments and recommendations set forth, and it was finally agreed that two motions should be made, (1) that the American Geophysical Union approves the revised Constitution and By-Laws of the American Geological Institute, and (2) that the suggested changes in the revised Constitution and By-Laws of the American Geological Institute set forth in the report be forwarded to the Institute with a request that they be given serious consideration. These motions were both adopted.

Membership--Chairman Hiatt reported that his Committee has now become organized and is planning to pursue the matter of securing more members among those qualified, and raised questions with regard to the best approach. He expressed the thought that the securing of new members can be best done by the members of the Union and that a few people scattered around the country in a Membership Committee tends to be cumbersome. He felt that there are certain areas where our membership is low and where special efforts might be devoted, and that in these states an active person might be selected to work with the Membership Committee in an effort to bring more of these into membership. He mentioned that another possibility is to request each member to secure a new member. Various comments were offered, among these being that qualified people are interested in knowing what membership means to them personally and that letters sent out to prospective members should be so oriented, and also that it would be better if we could indicate that there would be freedom from dues increase, say, for two or three years. Any incentive that is offered should be helpful. Others commented that they would prefer a dues increase to acceptance of persons not well qualified for membership. It was pointed out, however, that there is usually an optimum size for such an organization as ours and that ours should be somewhat larger than it is at present. We should seek out the young persons especially. It was mentioned that most of us have multiple memberships and that there is competition not only for dues but the time in reading publications. In order to compete in the latter point, our product must be superior. The idea of student membership was further discussed, and it was pointed out that this requires a change in the Statutes. It was further mentioned that there is a certain undesirability about our present format, notably the unjustified right-hand margin.

Budget--Chairman Beij presented the report of the Committee (see Appendix 2). This report was accepted, including the provision for joining in the retirement plan of the National Research Council. It was also noted that the Executive Secretary has received a grant from the National Science Foundation in partial payment of expenses to attend the Tenth General Assembly of the International Union of Geodesy and Geophysics, and it was voted that the Emergency Fund be drawn upon, if necessary, to the extent needed to defray complete necessary expenses.

Reports of Special Committees

Relations of American Geophysical Union with National Research Council--Chairman Berkner presented a report which, as it was adopted, appears as Appendix 3 (Section (11), which pertained to the discharge of the Committee, was deleted). There was extensive discussion of the report and of its provisions, and it was agreed that the Committee should be continued, and work out the final details with the Chairman and others concerned in the National Research Council.

Cosmic-Terrestrial Relationships--Chairman Stetson summarized the report shown in Appendix 4, which was accepted.

William Bowie Medal--L. H. Adams, Chairman, presented a brief report advising that, in line with past custom, the name of the recipient selected by the Committee would be revealed only at the time of the Award.

Award in Terrestrial Magnetism and Electricity--Chairman Fleming was not present, and as he is not at all well at present it has been suggested by members of the Committee, notably Reichelderfer, that Ross Gunn be designated as Chairman.

National Research Council

Division of Physical Sciences--Chairman O'Brien was not in attendance, but it was noted that a letter had been received from the Division of Physical Sciences inviting the AGU to appoint a representative to the Division with a relationship similar to the one now existing with the Division of Earth Sciences. It was approved that the President should make such an appointment.

Affiliated Organizations

American Geological Institute--It was noted that an application has been received from the American Association of Geology Teachers for membership in the Institute and that the constituent organizations are requested to indicate their desires with regard to such application. The organization was approved for membership.

American Association for the Advancement of Science--Representative Marble reported that at the last meeting of the Association in Boston in December, 1953, the American Geophysical Union had one session in its own name and co-sponsored three symposia. He expressed the feeling that AGU affiliation with the AAAS is mutually advantageous.

New Business

Recess--Recognizing the fact that there are likely to be further matters on which the Executive Committee should act during the Annual Meeting, it was voted that the meeting recess until immediately following the business meeting on Wednesday afternoon, May 5, 1954. The meeting recessed at 18h 45m.

John Putnam Marble, General Secretary
Waldo E. Smith, Executive Secretary

Second Session, May 5, 1954

The second session was called to order at 16h 48m in the Auditorium of the NAS-NRC Building, 2101 Constitution Avenue, Washington, D. C., by President James B. Macelwane.

Present--Twenty-eight persons were present as follows: John Adkins, L. R. Alldredge, W. W. Atwood, Jr., Robert Balk, Francis Birch, Walter H. Bucher, James J. Capello, Felix Chayes, E. A. Eckhardt, Maurice Ewing, R. H. Fleming, William F. Foshag, Ross R. Heinrich, Harry H. Hess, William E. Hiatt, Albert J Hoskinson, Woodrow C. Jacobs, Henry R. Joesting, Walter D. Lambert, James B. Macelwane, John Putnam Marble, James A. Peoples, Jr., Donald W. Pritchard, Waldo E. Smith, Victor Vacquier, Harold G. Wilm, James T. Wilson, and George P. Woollard.

It was noted that on the previous evening the following telegram was sent to Honorary President John A. Fleming, ill in Nashville:

> "On this Bowie Medal evening, your many friends and admirers in the American Geophysical Union send greetings and best wishes. We want you to know that our thoughts are with you more than ever."

Additions to General Secretary's Report

In connection with our representation on the Council of the AAAS, the AAAS has requested that our appointments be made on a calendar-year basis instead of on our usual fiscal-year basis. This will be adjusted as the terms of the incumbents approach completion.

It is also reported that the Bureau of Labor Statistics is now preparing a bulletin entitled "Manpower resources in geophysics, 1951." No Meteorology was mentioned in this booklet, and the plan is to issue a separate one on Meteorology. On our suggestion, appropriate entries are made at various points to cover the idea that Meteorology is not excluded from the broad geophysical field.

We have been cooperating with the geodesy group at Ohio State on matters of mutual interest relating to the Institute of Geodesy, Cartography, and Photogrammetry. W. A. Heiskanen is the Scientific Director.

It is suggested by the General Secretary that during the coming years when work on the International Geophysical Year is active it will be highly desirable for us to invite the Chairman of the United States National Committee to attend our Executive Committee meetings. Likewise the suggestion has been made that in order to establish close liaison between the URSI group and the AGU it will be desirable if the Chairman of the USA National Committee of URSI be invited to our Executive Committee meetings.

Word has come that some societies would like to have invitations to the Tenth General Assembly of IUGG. It is my understanding that it is contrary to policy to invite organizations to send representatives to these functions, but rather the U. S. National Committee, that is, the AGU functioning as a Committee might invite various individuals. The situation seems quite different from congresses wherein organizational representatives are the more common pattern. Suggestions on this point are requested.

In connection with matters relating to the NRC and to changes of names of Sections (see below), it will probably be necessary to send a ballot to our membership with respect to necessary changes in our Statutes and By-Laws. It is suggested that the Executive Committee take action to initiate this ballot. Along with the other changes cited above, it is recommended that this ballot should include an item to the effect that the Chairman of the Division of Geophysics of the National Academy of Sciences should be an ex officio member of our Executive Committee. It is also pertinent that the Statutes be revised to take account of the change in name of the Division of Geology and Geography to the Division of Earth Sciences. Also the changes in the Statutes should take cognizance of the fact that the old Division of International Relations cited in our Statutes and By-Laws is now non-existent and has been superseded by the Office of International Relations. It is recommended that the Director of that Office be designated as an ex officio member of our Executive Committee.

A number of years ago a committee brought in a favorable report relative to the establishment of a student grade of membership. While this was not rejected, it involved a change in Statutes which did not at that time seem warranted and a student subscription rate was established instead. There has been moderate use of the student subscription rate up to about 20 per year, but it has been mentioned that students are not inclined to become student subscribers and are much more inclined to become student members. The question is raised whether with changes in the Statutes and By-Laws it might not be desirable to place this item in the agenda.

John Putnam Marble, General Secretary

Action on the General Secretary's report--The report was accepted.

Motions were adopted authorizing the Committee on Statutes and By-Laws to proceed to make changes in our Statutes and By-Laws that are necessary in connection with the following matters, and after conferring with the officers of the Union that these recommended changes be offered to the membership by mail ballot without referring the wording to the Executive Committee:

(1) Those resulting from approval of report of Committee on Relations of AGU with NRC.
(2) The change in name of Division of Geology and Geography to Division of Earth Sciences.
(3) Making the Chairman of Section of Geophysics of National Academy of Sciences an ex officio member of Executive Committee.
(4) Changing Division of International Relations to Office of International Relations and designating Director of that Office as an ex officio member of Executive Committee.
(5) The change required with respect to a student grade of membership.

It was agreed that the International Union of Geodesy and Geophysics, constituted as it is, would act inappropriately if it sent invitations to various societies to send representatives or delegates to general assemblies. The general assemblies are not congresses but rather meetings in which the various National Committees join and the individual countries perform the necessary functions with respect to the operations of the International Union.

It was agreed that we should invite the Chairman of the United States National Committee for the International Geophysical Year and the Chairman of the USA National Committee of URSI to attend our Executive Committee meetings.

Reports of Sections

Terrestrial Magnetism and Electricity--It was reported that the International Association of Terrestrial Magnetism and Electricity is considering a name change to be more in conformance with the activity of the Association. The Section took action in this regard and recommends that if the name of the Association is changed to Geomagnetism and Ionospheric Physics, steps likewise be taken to change the name of our Section. It was agreed that this should be referred to the Committee on Statutes and By-Laws for appropriate change along with the items cited above.

Volcanology--The Section voted on May 4 unanimously to recommend that the name be changed to the Section of Volcanology, Geochemistry, and Petrology. This was likewise unanimously approved and referred to the Committee on Statutes and By-Laws for action.

In connection with the above changes, it was approved by the Executive Committee that the Committee on Statutes and By-Laws prepare the revisions in final form to put before a vote of the membership as promptly as possible.

Unfinished Business

There was further discussion of the matter of publication, and it was moved and approved that it is the sense of the Executive Committee that aggressive steps be taken to insure prompt publication of papers submitted and approved for publication in the Transactions of the American Geophysical Union. The further thought was expressed that we should attempt to reduce the period between receipt and publication to six months or less, if possible, and that on the basis of prompt publication we offer a definite inducement for use of the Transactions by authors which should outweigh any minor considerations of format to which there is now objection.

Adjournment--The meeting adjourned at 17h 40m.

John Putnam Marble, General Secretary
Waldo E. Smith, Executive Secretary

APPENDIX 1--REPORT OF THE COMMITTEE ON STATUTES AND BY-LAWS

K. Hilding Beij, Chairman

Ralph R. Bodle John A. Fleming

Your Committee, after consideration of the proposed new Constitution and By-Laws of the American Geological Institute submitted to member societies for approval, offers the following comments and recommendations.

(1) Name and scope of the Institute

Comments--Your Committee feels that both in the name of the Institute and in its announced purposes, the Earth sciences other than geology are not sufficiently emphasized. We feel, therefore, that member societies such as our own which are not primarily interested in geology may well feel dubious about being represented by the Institute acting as spokesman for their interests. Attention is called to Article II which states the purposes of the Institute as being: "To advance the interests of the geological professions; to promote cooperation of societies and other organizations active in the fields of the Earth sciences; to provide assistance to the geological profession in matters dependent upon united action; and to foster the application of the Earth sciences to human welfare." Also, Article III refers in paragraph 1 to "Earth sciences" and in paragraphs 2 and 3 to "geological sciences."

Recommendation--The name of the Institute should include a term such as "Earth sciences" or "geo-sciences" or "geophysics" in order to indicate the scope of the Institute's activities more clearly. In Articles II and III and in By-Law IX wherever the terms "geological sciences" or "Earth sciences" are mentioned singly, a complete term such as "geological and other Earth sciences" should be used. Definitions of these terms should be included. In Article II we feel that an additional purpose should be included, namely: "to promote the interests of the constituent organizations."

(2) Time of meetings

Comment--Article VI does not mention spring and fall meetings of the Board of Directors as stated in By-Law I.

Recommendation--Article VI should be amended to read: "Meetings of the Board of Directors shall be held in the spring and in the fall of each calendar year for the transaction . . ."

APPENDIX 2--REPORT OF THE COMMITTEE ON BUDGET FOR THE FISCAL YEAR ENDING JUNE 30, 1955

K. Hilding Beij, Chairman

Herbert N. Eaton	R. E. Gebhardt
John A. Fleming	Henry W. Hemple

Your Committee, on the basis of information supplied by the General and Executive Secretaries, proposes the following Budget for the fiscal year ending June 30, 1955.

The Union from time to time enters into contracts with other agencies, usually government agencies, for performance of work related to the interests of the Union such as bibliographies, symposia, manpower registers, etc. At present one contract is in force with the Air Force Cambridge Research Center for a Conference on Atmospheric Electricity to be held May 19-21, 1954, at Portsmouth, New Hampshire, and one is in prospect for a continuation of the Bibliography on Hydrology and Sedimentation. As these contracts are self-liquidating, they are regarded as extrabudgetary, and hence are not included here.

Your Committee believes that the financial status of the Union is now in sufficiently satisfactory state so that adequate provision for retirement benefits for the office staff can be made. It is impracticable to set up an independent retirement plan for such a small staff as ours. Fortunately, however, it appears that qualified members of our staff are eligible to participate in the retirement plan of the National Academy of Sciences. The Retirement Pension Trust Agreement of the Academy indicates that employees having two years service and being under 60.5 years of age may participate on a voluntary basis. Both the employee and the Union would be obligated to make contributions. For the first year or two the Union would be obligated to make an annual contribution of about $1,000. During the next five to ten years this annual contribution by the Union might conceivably rise to about $2,000. The Committee recommends that the Executive Committee approve this proposal and has therefore included the amount of $1,000 in the Budget for this purpose.

Operating Statement

Estimated receipts:			
National Research Council grant		$ 400	
Income:			
Dues	$36,100		
Sales of publications	7,500		
Sales of reprints	2,400		
Miscellaneous	300		
Interest	250	46,550	
From Reserve, Directory		900	
Total receipts			$47,850
Estimated expenditures:			
Publication of Transactions:			
Printing	$11,000		
Preparation	9,600		
Mailing	1,000		
Co-Editors	1,500	$23,100	
Reprints		2,200	
General office expenses:			
Salaries and Social Security	$15,300		
Retirement contribution	1,000		
Stationery and supplies	1,000		
Postage and communications	1,300		
Equipment	500	19,100	
Expenses for meetings:			
Annual	$ 700		
Regional	200	900	
Expenses, Sections		100	
Expenses, Committees		200	
Travel of officers		150	
Miscellaneous		100	
Directory:			
From Reserve	$ 900		
From Income	900	1,800	
Total expenditures			47,650
Estimated excess of receipts over expenditures			$ 200

Statement of assets as of June 30, 1954 and 1955 (both estimated)

		1954	Changes	1955
General Funds:				
Cash Reserve		$15,800	+ $200 from Income	$16,000
Reserve for Directory		900	- 900 for Directory	0
Permanent Fund:				
U. S. Bonds at cost	$2,368			
Northwestern Federal Savings and Loan Association	8,190	10,558	None	10,558
Emergency Fund:				
Prudential Building Association		1,052	None	1,052
Horton Fund		1,180	None	1,180
T. M. and E. Award Fund				
Liberty Building Association		210	None	210
Bills receivable less bills payable		2,500	None	2,500
Totals		$32,200		$31,500

(Note that the apparent decrease in assets is entirely due to the expenditure of the sum reserved for the Directory.)

APPENDIX 3--REPORT OF THE SPECIAL COMMITTEE ON RELATIONS BETWEEN THE AMERICAN GEOPHYSICAL UNION AND THE NATIONAL RESEARCH COUNCIL

L. V. Berkner, Chairman

Walter H. Bucher James B. Macelwane

(1) The formal organization of geophysics--The impressive growth of scientific exploration of the natural environment in which we live and move has generated the need for organization of communication among scientists to facilitate this exploration. Since scientific research into the natural phenomena of our terrestrial surroundings employs the tools and procedures of every natural science, and involves the common language of mathematics, the disciplinary synthesis of this research has come to be known as geophysics. Geophysics deals with the natural organization and the consequent forces inherent in the Earth's interior, its crust, its surface and its atmosphere, as well as the extraterrestrial influences on that natural organization. Because geophysics is not a single scientific discipline, but a synthesis of disciplines directed to the scientific attack on our natural environment, the organization of geophysics differs radically from the organization of a single science, such as physics or chemistry.

The birth of organized geophysics can be traced to the International Geodetic Association in 1864. The international origin of formal geophysical organization is no accident, for to geophysics the whole world must be its laboratory. Therefore, to employ this laboratory effectively, organized geophysical effort must supply not only the scientific communication common to other scientific development, but also the fundamental access to research in every political subdivision of the Earth, without which the important and more general problems of geophysics cannot be solved. This second requirement for universal geophysical access poses special problems of geophysical organization that are unique among the sciences.

The present synthesis of geophysics dates to the organization of the International Union of Geodesy and Geophysics (IUGG) which was founded in 1919 under the auspices of the International Research Council (subsequently the International Council of Scientific Unions (ICSU)). The IUGG represented a synthesis of previously independent international organizations in the fields of geophysics (International Geodetic Association, International Seismological Association, International Meteorological Committee, International Committee for the Study of Free Atmosphere, and International Commission of Terrestrial Magnetism). In common with the whole International Union movement, the IUGG is a non-political, non-governmental organization stemming from and governed by the grass roots movement among individual scientists. Nevertheless, individual governments must play an essential role in the Union structure to provide movement of scientists and their work across national boundaries, and to maintain the good offices of government in matters of support and communications. For these reasons, the adherence of individual scientists and their national organizations to the ICSU and the Unions is effectuated through the principal scientific Academy recognized by the government of each country. This relationship of the Unions to government is described in State Department Publication 3860 entitled "Science and Foreign Relations," May, 1950.

Even before the formal organization of IUGG, geophysicists of the United States acted through the newly organized U. S. National Research Council in 1918 to form a geophysical organizing committee under R. S. Woodward to ensure full United States participation and support of the embryo IUGG. Action through the NRC was in recognition of its status as the official United States adhering organization to the ICSU and its Unions. Formation of this committee led to the organization of the American Geophysical Union in 1920. The full history of the organization and subsequent development of the AGU is related authoritatively by John A. Fleming, Honorary President and long-time General Secretary of the AGU [Trans., v. 35, pp. 5-46, 1954].

With the healthy growth and development of the AGU together with the general evolution and orientation of American scientific organization, new organizational problems have emerged. These problems involve the interrelationship of the AGU and its parent body, the NRC, in the discharge of responsibilities of each organization. To ensure the solution of these problems in a manner consistent with the most fruitful development of geophysics, with adequate recognition of the responsibilities of the NRC, and with maintenance of the scientific and related political prestige of the United States, the President and Executive Committee of the AGU have initiated a series of studies looking to such further organizational alignments as may be appropriate. As a culmination of these studies, the present committee has been organized to submit specific recommendations for further organizational adjustments between NRC and AGU.

(2) Composition, responsibility, and authority of the Special Committee of AGU--On November 28, 1953, a Committee on Relations between AGU and NRC, under the chairmanship of F. W. Reichelderfer, reported to the Executive Committee of the AGU on relations between AGU and NRC. The Executive Committee adopted the recommendations of Reichelderfer's Committee that a Special Committee of the AGU be organized to carry on negotiations with the NRC. Accordingly on January 12, 1954, the President of the AGU appointed the following Special Committee on Relations between AGU and NRC: Walter H. Bucher, James B. Macelwane, and L. V. Berkner, Chairman. The Committee was instructed to examine all aspects of the evolving relations between AGU and NRC, and to report to the Executive Committee of the AGU those steps in organizational procedure that are deemed necessary and attainable toward achievement of the full effectiveness of the AGU in the discharge of its responsibilities. The Committee was authorized to negotiate with the NRC as necessary in the formulation of its report.

(3) Responsibilities of the AGU--The AGU acquires its responsibilities from its initial organization under the NRC. The word "Union" itself derives from the union of its basic responsibilities cited in the "Proposals for the Permanent Organization and Statutes of the AGU" by the Secretary, Harry O. Wood, on November 13, 1919:

> Thus, the American Geophysical Union, as proposed, is a union of two distinct committees, namely, the American National Committee of the International Geodetic and Geophysical Union, and the Committee on Geophysics of the National Research Council. In the absence of an American Geophysical Society in the United States, the proposed Union would seek to bring together and coordinate all societies, bodies, and institutions in the United States interested in geophysics.

Therefore, the AGU from its original organizational concepts combines the international responsibilities of the American National Committee of the IUGG and the national responsibilities of an "American Geophysical Society." In this latter role, it also bears a responsibility through the NRC to the U. S. Government for advice involving geophysics, acting as the NRC "Committee on Geophysics."

Your Committee believes it important to emphasize that in its development the activities of the AGU did not grow as two separate entities, that is, a "National Committee" and an "American Geophysical Society." This did not occur by accident. This union of responsibilities reflects the fact that in the field of geophysics the only logical "Society" is an international society, and is the IUGG. This situation reflects the special character of geophysics as the complex of scientific disciplines that deal with the Earth as a whole. Therefore, the AGU is really the "American Section" of the IUGG. The sponsorship of the AGU by the NRC reflects the dual role played by the AGU in discharging its responsibilities in an international sense through the NRC as the United States adhering organization to the ICSU and its Unions and its national responsibilities to the United States Government through the NRC as the agency responsible to the United States Government.

The national and regional meetings of the AGU bear a much stronger relationship to its position as an "American Section" of the IUGG than as an "American Geophysical Society." In these meetings, the AGU provides a forum of communication among American geophysicists whereby the progress of the science may be reported and assessed, and the character of continued international collaboration can be ascertained. The AGU is not an American scientific society in the ordinary sense, since its function depends so heavily on collaboration in international scientific observation at defined points over the Earth's surface coordinated by international organization. Almost every paper of the AGU Transactions implicitly involves the Earth as an entity. Thus, "The AGU serves international interests in studies of the Earth forces that condition human endeavor and progress . . . (involving) cooperation which is unrestricted by national boundaries." This point is emphasized since it underlies the special relationship justified between the AGU and the NRC, and not found essential in the NRC relationship with other scientific societies.

Originally, all responsibilities, both national and international, of the NRC were administratively discharged through the "Divisions" of the NRC. Consequently, in the "Proposals" of Wood (ibid):

> The present status of the American Section is that of a Committee of the Division of Physical Sciences of the National Research Council. This status it (the AGU) will retain until it is discharged as such, or until it is superseded by the adoption, as of some definite date, of proposals for permanent organization which change its status.

The limitation on this affiliation in light of the international character of AGU's responsibilities was recognized by the Organizing Committee at the time of the "Proposals" since they had further recommended:

> In this connection it has seemed best to the Committee on Organization to recommend that the proposed American Geophysical Union be made a Committee of the Council as a whole, and that the Union be so constituted as to unite and coordinate in our country the interests of physics, chemistry, and geology in geophysical questions. (Incidentally, astronomy, engineering, and mathematics might have well been included.)

In recognition of the soundness of these "Proposals," they were unanimously approved by the Executive Board of the National Research Council on December 20, 1919. On February 20, 1920, the American Geophysical Union was made a Committee of the Executive Board of the Council. This status remains unchanged.

(4) Evolution of the NRC in international affairs--In the earlier organization of the NRC, its international responsibilities were, in part, assumed by the old "Division of International Relations." Nevertheless, the National Committees of the International Unions continued to function largely through the Science "Divisions" of the NRC, even with respect to their international functions. Thus, while the Executive Committee of AGU was a Committee of the Council, its international responsibilities were largely channelled first through the Division of Physical Sciences and later partly through the Division of Geology and Geography.

By 1950, the character of world scientific collaboration had developed to the point where a more definitive organization within the NRC was needed to provide for the necessary international relationships. In particular, the problems imposed by the "cold war" made new organizational measures imperative within the NRC. At the request of the Secretary of State, A. N. Richards, then President of the National Academy of Sciences, appointed a special Committee under the Chairmanship of RogerAdams to consult with the Department on international scientific matters. In addition, the Chairman of the NRC, then Detlev Bronk, designated two Committees to cooperate with the Department of State in studying the several aspects of the problem. These two Committees produced reports of considerable consequence to the State Department Survey, entitled "NRC Report on Studies for the International Science Policy Survey of the Department of State" by Douglas Whitaker, and "The Report of the Committee on International Unions" by John A. Fleming. The impact of these reports on the State Department Survey led to the recommendation in "Science and Foreign Relations" (ibid):

> Since the National Research Council is so generally representative of American science it should act as a principal agent between private science and the Department of State. The Department will have to rely to a considerable degree upon the Council to advise regarding the dissemination of technical and scientific information that the Department desires to refer to appropriate scientists. Advice of the Council will be necessary in the matter of selection and briefing of delegates to scientific congresses. Its committees will be available, on short notice, to make special surveys of particular matters in the scientific and technical realm concerning which the Department requires the considered views of leading scientists. The National Research Council has indicated to the Survey its realization of the fact that it needs substantial reorganization in certain areas before it can meet the Department's requirements in the manner visualized. . . .
>
> Adequate contact with the National Research Council is prerequisite to the necessary liaison since the Council is the adhering agency for the United States in many international activities in science. There is no doubt that a more adequate organization of the Division of International Relations of NRC is necessary to the effectuation of this liaison; and the Council's report clearly implies its willingness to take positive action in this respect if the Department of State is prepared to work more closely with it.
>
> The elements of such liaison include:
> (a) Encouragement of wider support by science in the United States of international professional scientific and technological meetings.
> (b) Assistance in the formation of wholly adequate and representative United States delegations to reflect most effectively the needs and recommendations of science in the United States at such meetings; acquaintance of delegates with their responsibilities with respect to commitments involving the United States Government.

(c) Assistance in planning and organization of international meetings.

(d) Aid in the determination of the appropriate time and place for international meetings in the United States, in issuance of invitations for such meetings, and in the planning and conduct of such meetings.

(e) Acquisition by the Department of State of advance knowledge of administrative questions that may arise, full exploration of these questions with American science, and provision to American science of all information bearing on these questions and consequences of various courses of action.

(f) Aid in the effectuation of recommendations arising from international meetings.

As a consequence of these recommendations, the NRC established the Office of International Relations (OIR) in 1951 under the full-time directorship of W. W. Atwood, Jr. The "Division of International Relations" was abolished. At the same time the International Policy Committee of the NRC was established under the chairmanship of the then Foreign Secretary of the Academy, Roger Adams, to formulate the policies of governing the OIR. The NRC Committee on International Unions is organized under this Foreign Policy Committee.

In view of the time required for organization and orientation, the OIR is just now coming to full fruition. This office replaces the functions of the older "Divisions" of the Council in the discharge of the NRC's international administrative responsibilities. It provides a continuing Office with direct responsibility for dealing with our government, the ICSU and its Unions, as well as the Academies of other nations on matters of international organization. Therefore, the AGU must now look to the OIR of NRC as intermediary in its international administrative planning vis-a-vis the IUGG and other international agencies.

(5) Evolution of NRC in national affairs--In view of the transfer of NRC's international administrative responsibilities to the OIR, it is important to understand the remaining responsibilities of the Divisions of NRC to the AGU. The NRC has the responsibility to advise the United States Government on scientific matters upon request. In turn the NRC through its Divisions consults scientific organizations and forms special committees to consider such questions. Since the AGU is a Committee of the Council, it derives from this affiliation the responsibility for advice to the United States Government. This responsibility is discharged through the machinery of the Divisions.

Originally, stemming from the action of the original organizing Committee, the AGU had close relations with the Division of Physical Sciences. The evolution of the Council's affairs subsequently brought the AGU into close contact with the old Division of Geology and Geography. Consequently, the Executive Board of the National Research Council voted, on October 3, 1942, that the American Geophysical Union be invited to nominate a representative to be appointed to membership in the Division of Geology and Geography. The May 1, 1943, minutes of the annual meeting of the Division of Geology and Geography show that John A. Fleming was the first representative of the American Geophysical Union. At that time the membership of the Division of Geology and Geography was made up of these other organizations: American Association of Petroleum Geologists, American Ceramic Society, American Geographical Society, Association of American Geographers, Geological Society of America, Mineralogical Society of America, Paleontological Society, and Society of Economic Geologists.

The organizations represented in the membership of this Division have changed somewhat during the past 11 years, the American Ceramic Society having dropped out and six other organizations having been added; but the American Geophysical Union has been represented continuously throughout this period.

In 1953, as a consequence of recommendation of the Chairman of the NRC, a new Division known as the Division of Earth Sciences was established by the Academy within the NRC organization to supersede the Division of Geology and Geography. This Division embraces the interests of geology, geography, and exploration geophysics, and is really a recognition of the important role of "exploration geophysics" in the development of our natural resources.

Therefore, in certain respects, the Division of Earth Sciences may be considered the principal agency of the NRC that will consult the AGU and its members in providing advice on geophysical matters to the United States Government. In seeking to provide such advice, however, any Division of the NRC is free and has the responsibility to consult the AGU on geophysical matters, and such requests are not limited to the Division of Earth Sciences. In fact, the geophysical interests and contributions of the AGU extend deeply into the fields of physics, chemistry, astronomy, engineering, and mathematics, as well as geology, geography, and geophysical prospecting.

This breadth of competence of the AGU is fully recognized by the NRC. Thus, as the result of informal discussions in the past year, the American Geophysical Union, now represented by membership in the renamed Division of Earth Sciences, and the American Meteorological Society, now represented by membership in the Division of Physical Sciences, have each been invited to have representatives in the membership of both of these two Divisions of the Research Council. Moreover, there is no bar to representation by the AGU on other Divisions of the Council, should the need arise, and your Committee believes that any request for such representation would be considered sympathetically by the Council, if based on substantial grounds.

(6) Basic relationship of NRC to AGU--In spite of the fact that this recitation of events leaves no doubt as to the actual status of AGU, there appears to remain a certain confusion in the minds of many as to the actual relation of AGU to NRC. In spite of the action of the Council on February 20, 1920, already cited in section (3), there has been a widely accepted feeling that the AGU is responsible to the Division of Earth Sciences of the Council rather than to the Executive Board of the Council. This perhaps arises as a consequence of the earlier relations of the AGU to the Division of Geology and Geography, and to the Division of Physical Sciences with respect to arrangements for international meetings. Both the NRC and the AGU are agreed that such an interpretation does not recognize the relations of the AGU to the OIR, NRC, in all international administrative aspects, nor the International Policy Committee on policy aspects of international relations, which are principal concerns of the AGU, nor does it recognize the scientific content of geophysical science with respect to the several Divisions of the Council.

Your Committee believes that events have demonstrated the wisdom of the original organizing committee quoted in section (4) of this report in recommending that the Executive Committee of the AGU be a Committee of the Council. Such a line of responsibility does not preclude the direct lines of communication to the Divisions and to the OIR as recommended subsequently in this report. It does recognize that not all science is definable in a vertical line organization, and that geophysics cuts across the vertical lines of scientific organization and endeavor. It does avoid forcing the organization of science into a rigid pattern dictated by administrative convenience.

Therefore, your Committee believes that to avoid any further confusion, the following reaffirmation should be made by the Executive Committee of the AGU to the Chairman of the NRC:

> In recognition of the predominantly international character of the work of the AGU, and the synthesis of the natural sciences involved in the conduct of geophysical research under its aegis, it is the understanding of the AGU, in consonance with the action of the Executive Board of the Council on February 20, 1920, that the Executive Committee of the AGU remains as a direct Committee of the Council.

(7) Additional clarifying organizational measures by NRC--To formalize working communication between the AGU and the NRC your Committee proposes the following further recommendations.

> The Chairman of NRC, by appropriate action, is asked to clarify the detailed working relationship between the AGU and NRC by defining this relationship as follows:
>
> (a) The AGU shall consider the Office of International Relations to be the responsible agency of NRC in all international administrative matters, and in view of the AGU's predominantly international interests should consider this Office as its principal administrative contact with NRC.
>
> (b) The AGU should refer all international policy matters requiring clarification or definition through the Chairman of the NRC to the NRC "International Policy Committee."
>
> (c) The AGU is invited to retain representation on the Divisions of Earth Sciences and of Physical Sciences. The AGU and its membership will be responsible to the several Divisions of the NRC for aiding the NRC in discharge of responsibilities to the United States Government for the provision of scientific information within its purview. In this respect, the Divisions of NRC may form special committees to aid in this process that include AGU members and acting through the AGU representatives to the Division as appropriate and may call upon the AGU for such assistance as may be deemed desirable.

(8) Organization for international meetings--During the earlier years of IUGG, the organization of delegations to international assemblies proved a simple matter. In essence, the AGU-NRC simply supported those eminent geophysicists who could find their own travel allowances. In a few cases, the good offices of the AGU influenced provision of travel support for an especially deserving scientist. Thus, the selection of the delegation was a simple matter and, under the present Statutes of the AGU, "The Executive Committee, in consultation with the Sections, shall nominate

to the Executive Board of the NRC delegates, or representatives, to the Assemblies and Meetings of IUGG and of its Associations . . .'' The present Executive Committee consists of some 40 members, embodying all officers of the Union and of its Sections, as well as United States citizens who are officers of the IUGG and its Associations, and others.

The designation of an international delegation has now been complicated by a number of factors. These are partially summarized in the report, ''Science and Foreign Relations.''

> The Department of State adheres to a fundamental policy of non-interference with intellectual freedom of scientific discussion. However, the Department of State has a considerable stake in certain administrative matters in connection with the international meetings, such as:
>
> (a) The extent of United States participation and financial support and the desirability or necessity for increasing or modifying this support.
>
> (b) The issuance of invitations for future meetings in the United States and provision or support of funds needed to underwrite such invitations.
>
> (c) Matters affecting the adequate organizational aspects of the conference in the interests of its objectives.
>
> . . . Explicit instructions of this type are rarely given to official or other delegations to meetings of non-governmental organizations, but the views of the Department may be made known informally to the chairman and other members of such a delegation, or may be reflected by officers of the Government who are members of the delegation.
>
> The agenda of each conference and meeting should be studied in advance for administrative implications of interest to the United States Government so that delegates may undertake adequate advance preparation. This should include the encouragement of positive measures . . . United States delegations are frequently less than completely prepared to represent their country on the administrative issues at hand. These defects could be remedied through development of briefing procedures by the National Research Council working in close conjunction with the Department of State. The National Research Council should be prepared to assume full responsibility for the preparation of United States delegations, and to advise the Department of State on all matters on which a formal government position will be necessary. The Department of State should participate in these procedures to the extent necessary to advise on all corollary matters. The National Research Council should be urged to take initiative to assume the development of well-organized, well-prepared, and well-briefed delegations.

These comments are especially cogent at this time when (a) revision of the structure of ICSU and the general interrelationship of world scientific organizations is under consideration; (b) the United States has under consideration certain radical proposals for change in the payment of dues to ICSU and its Unions to strengthen their position; (c) the sponsorship of specific international scientific activities by agreement with UNESCO falls to ICSU and its Unions, involving fiscal decisions of considerable moment; and (d) the organization of world geophysical research activities depends substantially on the collaboration and support of diverse United States Government agencies.

Because of such responsibilities whose discharge involves a clear understanding of the consequent fiscal responsibilities that are inevitably involved, the government requires a minimum level of experience on the ''voting'' membership of Union delegations. (Each national delegation to a Union Assembly is assigned a certain number of ''votes'' on administrative matters. These are of importance in consideration of administrative and fiscal matters but have no relation to scientific aspects of the Assembly.)

Moreover, the spectacular growth of geophysical activity has engaged the attention of a number of other organizations outside the AGU which are working intensively and effectively in the field of geophysics. These organizations also have an interest in the delegations to International Assemblies of the IUGG.

The Department of State has delegated to the NRC the responsibility for selection of delegations that not only include United States leadership of geophysical science, but also contain a minimum knowledge and competence concerning the administrative and fiscal responsibilities that may emerge as a consequence of the Assemblies. Under its Statutes, the AGU has the responsibility for making the recommendations for composition of the delegation to the NRC.

Considering the complexity of factors leading to the selection of the delegation, the present Executive Committee of AGU appears too unwieldy to give these factors the intimate consideration that is now required.

Your Committee therefore proposes that by extension of the By-Laws of the AGU:

> A Standing Committee of the AGU on International Participation shall be formed to consist of six persons (not necessarily members) who shall be eminent geophysicists with knowledge and background in international scientific organization and cooperation. The President and the General and Executive Secretaries of the Union shall be ex-officio members of this Committee. The Committee shall be appointed at the first meeting of the Executive Committee following each Assembly of the IUGG and shall serve for the term of three years, to include the interval of the next Assembly.
>
> It shall be the duty of the Committee, acting on behalf of the Executive Committee, (a) to recommend to the OIR, NRC the organization of delegations to the Assemblies of IUGG and to such other international scientific meetings as may be appropriate; (b) to review all administrative questions that might or should be raised at, or may be related to, international meetings or assemblies with the view to fully informing our delegations of the implications thereof; and (c) to advise the NRC Foreign Policy Committee, or the NRC Committee on International Unions, on matters of international science policy relating to geophysical science.
>
> The Committee shall advise the Executive Committee of the AGU of all actions taken or initiated.
>
> In acting, the Committee shall take full account of the broad interests of geophysical science in the United States, and of the various organizations and agencies involved in geophysical activity.

(9) The home of the AGU--For many years, establishment of an official headquarters for the AGU has been a matter of concern. Through the generous support of the Carnegie Institution of Washington, offices at their headquarters at 1530 P Street have been provided as a stop-gap measure. However, all parties recognize this arrangement as a temporary expedient.

The necessary close relationship of the AGU to the NRC dictates that the ultimate solution should be the provision for the central AGU office by the NRC under circumstances that bring it into close relationship with the OIR of the NRC. Moreover, during special international scientific operations in which the Union has a vital interest, such as the International Geophysical Year, which is directly sponsored by the NAS-NRC, arrangements for the office of the permanent Secretary for the U. S. National Committee, IGY, were temporarily provided by the National Science Foundation.

The main requirement is one of office space in the same building as the OIR, NRC. No single center exists in which the various international scientific activities of American science can be centralized.

In recognition of this, among other needs, the OIR has made specific proposals to the Foreign Policy Committee, NRC, to provide for aid to the United States scientific organizations that bear responsibility for international scientific participation. The report of OIR states:

> To strengthen and improve the structures and procedures by which United States scientists participate in international organizations, the Academy wishes to provide greater support for the national committees of international scientific unions. In addition, it wishes to establish new national committees as the need arises. At the present time the Academy sponsors eight such committees, but approximately twenty are needed.

This report has not yet been adopted, awaiting completion of active measures toward raising the necessary funds. However, the President of the Academy and the Chairman of the Council have carefully reviewed these proposals, and your Committee is informed that serious efforts are being undertaken to finance the proposals of this program.

While the report does not specifically discuss the need for centralized housing of international activities, this is not precluded as one means of support. Activities involving actual participation of the AGU or its representatives in international affairs are considered to be the financial responsibility of the NRC. On the other hand, the AGU retains financial responsibility for its national activities. Your Committee has noted the firm Executive Committee policy of the AGU to remain self-supporting financially with respect to all of its national activities, beyond the problem of the housing of its administrative staff. Moreover, the membership of the AGU has accepted the steadily increasing dues in support of this policy. Therefore, the need for NAS-NRC support for the AGU derives principally from the need for headquarters housing. Fulfillment of this need would also aid the NRC in the discharge of its international responsibilities by providing proximity, mutual aid, and more intimate joint planning.

Joint housing of all international activities under the NRC has much in its favor. The very existence of such a center would go far toward simplifying the task of the foreign visitors to the United States. It would permit extension of mutual aid among the several staffs in preparation for international meetings. It would avoid misunderstandings that now grow out of lack of communication among the staffs and officers of various United States National Committees with the OIR. It would be a focal point in determining United States policy relating to ICSU and its Unions. It would provide better communication through such media as the NRC Newsletter on international matters. Because of better communications, it would simplify relations with the Department of State, the National Science Foundation, and the Department of Defense, and other government agencies that inevitably are involved in international scientific activities. Briefly, such a center for NRC international activities would go far to keep our several international scientific activities from stumbling over one another in performance of their tasks.

The imposing and dignified architecture and situation of the present home of the NAS-NRC is ideally suited to the symbolic representation of United States participation in international scientific activity. Moreover, international participation in science is intimately related to the basic purposes and day-to-day activities of the Academy. Therefore, it is to be hoped that by extension of the present structure, or other rearrangement of the activities that it presently houses, the Academy building might eventually house this "Center for International Scientific Participation."

Your Committee believes that the proposal for housing the AGU together with other NRC international activities might well receive favorable consideration by the Council. In making such a proposal, the AGU must recognize that time would be required to bring such a plan to fruition, and its proposal must be tempered by some patience and a large measure of cooperation. Your Committee believes that, providing the staff of the AGU does not grow substantially beyond its present size, the NRC would look favorably on a long-range plan to house together both the national and international headquarters activities of the AGU.

Therefore, the Committee recommends that the following proposal be made to the NRC:

> "In view of the common interests and objectives of the AGU acting in concert with the NRC, the AGU suggests that consideration be given by the NRC in its long-range planning to provision of housing for the AGU's administrative staff in close proximity to the OIR. More generally, the AGU believes that the creation of a 'Center for International Scientific Participation' to bring together the OIR with the several international activities for which the NRC is ultimately responsible would provide a most salutory step in encouraging international scientific collaboration."

(10) Summary of recommendations--Summarizing the studies of your Committee, it recommends that the following communication be made to the Chairman of the National Research Council:

The Executive Committee, AGU, has reviewed the relationship of the AGU to the NRC with the view to clarifying certain confusion that appears to have arisen in the past. In recognition of the predominantly international character of the work of the AGU, and the synthesis of the natural sciences involved in the conduct of geophysical research under its aegis, it is the understanding of the AGU, in consonance with the action of the Executive Board of the Council on February 20, 1920, that the Executive Committee of the AGU remains as a direct Committee of the Council. (From section (6) of this report.)

The Chairman of the NRC, by appropriate action, is asked to clarify the detailed working relationship between the AGU and NRC by defining this relationship as follows:

(a) The AGU shall consider the Office of International Relations to be the responsible agency of NRC in all international administrative matters, and in view of the AGU's predominantly international interests should consider this office as its principal administrative contact with NRC.

(b) The AGU should refer all international policy matters requiring clarification or definition through the Chairman of the NRC to the NRC "International Policy Committee".

(c) The AGU is invited to retain representation on the Divisions of Earth Sciences and of Physical Sciences. The AGU and its membership will be responsible to the several Divisions of the NRC for aiding the NRC in discharge of responsibilities to the United States Government for the provision of scientific information within its purview. In this respect, the Divisions of NRC may form special committees to aid in this process that include AGU members and, acting through the AGU representatives to the Division as appropriate, may call upon the AGU for such assistance as may be deemed desirable. (From section (7) of this report.)

In view of the common interests and objectives of the AGU acting in concert with the NRC, the AGU suggests that consideration be given by the NRC in its long-range planning to provision of housing for the AGU's administrative staff in close proximity to the OIR. More generally, the AGU believes that the creation of a "Center for International Scientific Participation" to bring together the OIR with the several international activities for which the NRC is ultimately responsible would provide a most salutory step in encouraging international scientific collaboration. (From section (9) of this report.)

Your Committee further recommends that the Executive Committee act to extend the By-Laws of the AGU as follows:

> A Standing Committee of the AGU on International Participation shall be formed to consist of six persons (not necessarily members) who shall be eminent geophysicists with knowledge and background in international scientific organization and cooperation. The President and the General and Executive Secretaries of the Union shall be ex-officio members of this committee. The Committee shall be appointed at the first meeting of the Executive Committee following each Assembly of the IUGG, and shall serve for a term of three years, to include the interval of the next Assembly.
>
> It shall be the duty of the Committee, acting on behalf of the Executive Committee (a) to recommend to the OIR, NRC, the organization of delegations to the Assemblies of IUGG and to such other international scientific meetings as may be appropriate; (b) to review all administrative questions that might or should be raised at, or may be related to, international meetings or assemblies with the view to fully informing our delegations of the implications thereof; and (c) to advise the NRC Foreign Policy Committee, or the NRC Committee on International Unions, on matters of international science policy relating to geophysical science.
>
> The Committee shall advise the Executive Committee of the AGU of all actions taken or initiated.
>
> In acting, the Committee shall take full account of the broad interests of geophysical science in the United States, and of the various organizations and agencies involved in geophysical activity. (From section (8) of this report.)

APPENDIX 4--REPORT OF THE SPECIAL COMMITTEE ON COSMIC-TERRESTRIAL RELATIONSHIPS FOR THE YEAR ENDING JUNE 30, 1954

Harlan T. Stetson, Chairman
E. O. Hulburt, Vice Chairman

Ross Gunn	Robert R. McMath	Herbert Riehl	Harry W. Wells
Serge A. Korff	Donald B. Menzel	W. T. Thom, Jr.	

At the beginning of the fiscal year the Special Committee on Cosmic-Terrestrial Relationships was reappointed for the triennium 1953-56, and is constituted as above. A brief interim report was made to the Executive Committee at its meeting in Washington in November, 1953.

The fields in which the Committee is now concerned include solar investigation, upper-air research, problems of the ionosphere, radio astronomy, meteorological relations, and cosmic-ray investigations. An important and comprehensive volume entitled The Sun, by a board of experts and edited by Gerard P. Kuiper, was published by the University of Chicago Press in 1953. Sections of this volume provide a compendium to the students of Solar Terrestrial Relationships, including solar radio-frequency emissions.

Solar activity during the year has remained remarkedly low, the Zurich monthly sunspot number reaching a value of 0.0 in January, 1954. The continuity of many days in which no sunspots were observed has afforded the opportunity for the study of geomagnetic and ionospheric phenomena free from any great disturbances accompanying any conspicuous solar activity. A communication received from W. Gleissberg ventures a prediction for the next sunspot maximum as of June, 1958.

Through the courtesy of Helen W. Dodson, the McMath-Hulbert Observatory of the University of Michigan, reports activities to our Committee as follows:

The program of basic solar research has been continued at the McMath-Hulbert Observatory. Observations and analyses of the solar spectrum at high dispersion in both the infrared and photographic regions have been carried out at Lake Angelus and at Mount Wilson with the Snow telescope. Construction is under way of a very high dispersion vacuum spectrograph for use at Lake Angelus.

Continuous monochromatic, photographic studies of rapidly changing solar features have been continued. During the last year solar activity was at a low level as the minimum in the sunspot cycle was approached. On August 13, 1953, the first sunspot of the new cycle was observed in latitude N 52°. The next two spots of the new cycle were observed on February 8-9 and March 1-2, 1954, in latitudes N 31° and S 26° respectively. In addition, at least five small spotless plages with latitudes greater than 30° were visible on calcium spectroheliograms for two or more successive days.

Studies of the intensity, area, and position of flares have been continued. Photometric light curves have made possible measures of rates of rise and decline as well as maximum intensity. Theoretical studies have shown that the greatly widened $H\alpha$ line observed in some flares can be explained by radiation damping. Study of the width of $H\alpha$ in flares as reported in the Quarterly Bulletin of Solar Activity has indicated that $H\alpha$ width increases with central meridian distance of the flare.

Further cooperative studies with the radio astronomers at Cornell University and the National Research Council of Canada have been carried out. The Cornell records have been examined for all onsets and sudden increases in the 200 Mc/sec noise storms. This new study confirms our earlier report that these 200 Mc/sec events are flare-associated and start late in the course of the flare, after $H\alpha$ maximum has been attained and as the flare is fading or over. Photometric studies of calcium spectroheliograms for October 16, 1951, have shown that the positions of the three maxima in the distribution of calcium plages coincided closely with the positions of the three regions of excess 2800 Mc/sec radiation observed at Ottawa on this date. Only two of the three plages had sunspots associated with them.

Charts containing solar, ionospheric, and geomagnetic data have been kept up to date. In order to make immediate comparisons between disturbances in the ionosphere, the geomagnetic field, and observed changes on the Sun, two new instruments have been installed at the Observatory. One is a total field variometer that records certain aspects of the variation in the Earth's magnetic field; the second is an instrument that measures the intensity of the 5 Mc/sec WWV signal as received at Lake Angelus.

Donald B. Menzel, Director of the Harvard College Observatory and cooperating stations, makes the following comments relative to the Observatory's solar research: I feel that the most significant contributions that we have made at Harvard and at our associated observatories lie in the interpretation of solar phenomena in terms of magneto-hydrodynamics. First of all, we have developed a system of classification of solar prominences in terms of their behavior. The system is still preliminary and is being tested out by my students. We do find that it works fairly well, though some revision of the original plan is required. Anyway, we find a distinct difference between prominences that appear in the spot zones and in the non-spot zones. Second, we notice a great difference in the prominences where material tends to come from above and where much of the motion comes from below. Finally, we have increasing evidence that the motive force for the expulsion of material from the Sun or sunspots is an intense electric current flowing in the ionized gas. To phrase it literally, but popularly, one can almost say that the Sun "blows a fuse." In any case, as is well known from electrodynamics, a current loop tends to increase its radius and also exerts a pressure on the wire that would attempt to decrease the size of the wire if that were possible. Since in the solar atmosphere the "wires" are made of gas, the "pinch effect" is notable in many prominences. Indeed, I attribute most of the fine filaments of prominences to the presence of currents.

One further element of understanding that I have been arguing for is the peculiar nature of the motion of knots in prominences. These knots are sometimes attributed to gas moving along a magnetic field. In other words, the motion of the gas is supposed to map out the lines of force. With this interpretation I strongly disagree. In fact, if anything, the motion is more nearly perpendicular to the lines of force than parallel to them. There are many subtle arguments that favor my conclusion, but I think it is important in our knowledge of the Sun to realize that flow of material follows the line of a current rather than the line of a magnetic field.

I have been arguing that loops of current, held together by the pinch effect, actually exist between the Earth and the Sun. These dynamic doughnuts ring the Earth and cause magnetic storms, aurora borealis displays, etc. The details are complicated, but we are still working on them. I should mention that these phenomena all have an effect on ionospheric radio propagation as well. For example, the pinching down of the gas in the neighborhood of sunspots sometimes occurs with the force of shock waves and results in the release of enormous amounts of ultraviolet radiation in a short time. This ionization is responsible for the sudden ionospheric disturbances.

In brief, we are beginning to understand more of the nature of solar activity, although there is still a great deal for us to learn.

The program of the Naval Research Laboratory includes important topics in cosmic-terrestrial relations for which E. O. Hulburt, Director of Research, provides the following summary.

Upper atmosphere rocket work--By means of rocket-borne equipment the solar spectrum was photographed to 1800 A, with a resolution varying from 0.3 A at 2800 to 0.9 A at 2100 A, and to a rather low value at 1800 A. The analysis of the spectrum from 2990 A to 2635 A was completed, with about 500 lines, and 1054 probable contributors listed; this will appear in the Astrophysical Journal in 1954 in a paper by D. E. Wilson, R. Tousey, J. D. Purcell, F. S. Johnson, and C. E. Moore.

The solar-intensity distribution from 3400 A to 2200 A was derived from the rocket spectra; in the range 3000 A to 6000 A new data were obtained by Dunkelman and Scolnik from Mount Lemmon, Arizona; the entire solar curve and its relation to the Smithsonian work on the solar constant were considered, and a new value, 2.00 cal/cm^2 min, proposed for the solar constant. This was described briefly by F. S. Johnson, J. D. Purcell, and R. Tousey in the Proceedings of the Gassiot Committee meetings, Oxford, 1953. Detailed papers on the various phases will appear in 1954.

The diurnal heating effect in the upper atmosphere due to absorption of solar energy by ozone was computed from ozone distribution and solar-energy distribution data obtained from the rocket flight of June, 1949 [F. S. JOHNSON, Bull. Amer. Met. Soc., v. 34, pp. 106-110, 1953].

Measurements of solar radiation by means of rocket-borne photon counters [E. T. BYRAM, T. CHUBB, H. FRIEDMAN, and N. GAILOR, Phys. Rev., v. 91, p. 1278, 1953; v. 92, p. 1066, 1953] showed: (1) The intensity of the Lyman alpha line of hydrogen from a quiet Sun is 0.1 erg/cm^2 sec; it is an emission line of width less than 1 A, superimposed on a background continuum effectively less in intensity than a 4500° K blackbody Sun. (2) The continuum near 1500 A is abruptly absorbed near 100 km, in agreement with a rapid transition from molecular to atomic oxygen near this level. (3) The shape of the x-ray spectrum is consistent with a 10^6 degree temperature in the corona; soft x-ray intensities of the order of 0.1 erg/cm^2 sec were observed from a quiet Sun and as much as 1 or 2 erg/cm^2 sec from an active Sun; these intensities are adequate to account for E-layer ionization and absorption was observed to occur in the correct range of altitudes.

The program to determine upper atmospheric pressure, temperature, and density values was extended to the Arctic regions during the summer of 1953. Measurements were made at 74°, 62°, and 43° N. A new technique in meteorological research was developed and used; altitudes up to 80 km were reached with a relatively inexpensive rocket launched from a skyhook balloon at 25 km above sea level. Preliminary analysis of the flights at 74° N indicates that the Arctic density values for the 25 to 40 km altitude region are about equal to those measured in rocket flights at White Sands.

The composition of the upper atmosphere between 95.8 km and 137.3 km above sea level has been studied by means of a Bennett radio-frequency mass spectrometer. The spectrometer, installed in an Aerobee rocket launched at White Sands Proving Ground, New Mexico, at 09h 00m (MST) on February 12, 1953, measured the relative abundance of all gases between mass numbers 54 and 6 on the ascent and descent of the rocket. One hundred seventy-two individual traverses of this mass range were made at a rate of 0.94 per second. The data show that the ratio of argon to molecular nitrogen failed to change as a function of altitude in a manner consistent with the existence of diffusive separation.

The results of radio propagation experiments in the ionosphere were published. The electron density increased rapidly between 92 and 110 km and remained at a large value above 110 km, indicating that the E-layer probably remains dense up to the F-layer during the daytime. Values of the Earth's magnetic field observed at 105 and 139 km were found to agree with the inverse cube law. The data from two flights showed that the Lorentz polarization term should not be used at four megacycles in the Appleton-Hartree formula. The September, 1949, flight showed the existence of an ion layer between 80 and 95 km with a maximum of 5×10^8 ion/cc at 91 km. Collision frequencies computed at 105 and 139 km were in agreement with values obtained from ground measurements [J. C. SEDDON, J. Geophys. Res., v. 58, pp. 323-335, 1953].

Cosmic-ray work from balloons--Observations in stratosphere-exposed nuclear emulsions of the production and decay of charged hyperons (particles intermediate in mass between proton and deuteron) show that these particles can originate in fundamental-type collisions between nucleons [M. SHAPIRO, Science, v. 118, p. 701, 1953]. The decay scheme fits the observations and leads to a computed mass of 2650 electron masses. Evidence that the charged secondary is a pion indicates that the same is probably true in the "V-particle cascades" observed in the cloud chambers at Pasadena and Manchester [D. T. KING, N. SEAMAN, and M. SHAPIRO, Phys. Rev., v. 92, p. 838, 1953]. A "constant sagitta" method of multiple scattering has been applied to the tracks of stopped K-mesons (including tau), hyperons, protons, and pions. Mass estimates for slow K-mesons thus far yield values of $\approx 1000\ m_e$. The first known example of an emulsion tau decay found in a United States laboratory has been observed in the course of this study. Measurements of the cross section for the production of tridents have yielded agreement with Racah's theory [W. WADA and D. T. KING, Bull. Amer. Phys. Soc., v. 28, p. 10, 1953].

Radio astronomy--Radial brightness distribution curves taken with the 50-ft radio telescope at a wavelength of eight mm, where the resolution is three minutes of arc, showed limb brightening. These results give greater weight to the model of the Sun's atmosphere derived from earlier radio work and show a sharp rise in temperature at the top of the chromosphere. Enhanced radiation from localized regions associated with sunspots has been identified both in the eclipse records and in the drift curves taken at high resolution with the 50-ft radio telescope.

Observations at nine cm with the 50-ft telescope have revealed ten radio stars, seven of which are in the galaxy and three are extra-galactic. Of the seven there are four which are of a new type and emit more energy at nine cm than at the longer wavelengths. This is the first detection of the radio-frequency emission of "hot" hydrogen regions such as the Orion Nebula and can lead to a better knowledge of the temperature and density of the clouds. Apparatus for observing line emission from neutral hydrogen is also installed in the 50-ft radio telescope. It is intended to make use of the higher resolution obtained to make detailed studies of selected regions of the galactic hydrogen clouds.

Twilight sky brightness--Measurements were made of the brightness and polarization of the twilight sky during clear weather at various points over the sky for altitudes of the Sun from five degrees above the horizon to 15° below the horizon at two stations, one in Maryland at an altitude of 100 ft and one on Sacramento Peak, New Mexico, at an altitude of 9500 ft. The brightness of the Sacramento Peak sky was about 2/3 to 1/2 that of the Maryland sky because of lesser haze [M. J. KOOMEN, C. LOCK, D. M. PACKER, R. SCOLNIK, and E. O. HULBURT, J. Opt. Soc. Amer., v. 52, pp. 353-356, 1952]. Theoretical calculation showed that the brightness and color of the zenith twilight sky was controlled by upper atmospheric ozone in an important manner [E. O. HULBURT, J. Opt. Soc. Amer., v. 43, pp. 113-118, 1953].

Solar eclipse, February 25, 1952--The total solar eclipse of February 25, 1952, was observed at Khartoum, Sudan. Solar limb brightening in radio wavelengths ten cm and eight cm was observed and measured [J. P. HAGEN and Others, Astrophys. J., in press]. Solar limb darkening in optical wavelengths from 3800 to 5800 A and at about 8000 A was observed and measured [F. J. SEYDEN and Others, Astrophys. J., v. 118, pp. 412-428, 1953].

Aurora theory--Making use of the new observations of A. B. Meinel that protons enter the upper atmosphere at the commencement of an auroral display, a new auroral theory was worked out based on the magnetic self-focussing action of ionized streams. Such a stream will be bent into auroral zones, in agreement with the calculations of Störmer. The amount of focussing into the stream depends on the rate of emission of ionized particles from the Sun and on the density of the ionization (assumed to be electrically neutral) in the region between the Sun and the Earth. Quantitative estimates appear reasonable [W. H. BENNETT and E. O. HULBURT, Phys. Rev., v. 91, p. 1562, 1953].

Studies of solar relationships to radio-wave propagation has continued to be a major topic of interest to the Central Radio Propagation Laboratory of the National Bureau of Standards. Many of the results have been published in detail in the research papers of the National Bureau of

Standards, in the Proceedings of the Institute of Radio Engineers, the Journal of Geophysics, and in other scientific and technical publications.

H. W. Wells of the Department of Terrestrial Magnetism states that studies of traveling disturbances in the E- and F-layer regions of the ionosphere have continued. It appears that F-layer region disturbances move predominantly from west to east with velocities of 100 to 200 meters per second. Dimensions of "ionic clouds" appear to lie between 200 and 400 km.

The Department is now engaged in a program of radio astronomy using interferometers at 200 mc/sec for the study of radio emissions both from the quiet Sun and from active areas associated with sunspots. It appears that certain types of solar radio noise may be definitely identified with visible features on the Sun.

The study of radio-star scintillations demonstrate the existence of irregular refraction processes in the Earth's outer atmosphere. Such studies promise a new tool for investigation of the electrical properties of our atmosphere.

Further details of cosmic investigations are to be found in the annual report of the Director of the Department of Terrestrial Magnetism.

For those further interested in cosmic effects upon radio wave propagation, the Committee calls attention to the reports of the Annual Review Committee of the Institute of Radio Engineers appearing each year in the April issue of the Proceedings. Such comprehensive reports cover the fields of both ionospheric and tropospheric propagation, not only in this country but abroad. These reports are invaluable to researchers in the field of Cosmic-Terrestrial Relationships, including radio astronomy.

In the field of Meteorology, Herbert Riehl reports activities of the Chicago group as follows: Since meteorological sounding balloons have started to penetrate to the middle stratosphere on a regular basis at several stations, they have recorded large temperature changes from time to time which have not been considered readily explainable in terms of "normally accepted" meteorological processes. The simultaneous improvement of solar-radiation measurements has led to wide-spread research into solar-terrestrial relations in the last few years.

Some correlations have been noted between solar variations and anomalous changes of weather and wind field in the lower atmosphere. The solar changes investigated are (1) those of ultraviolet radiation thought to affect the equatorial stratosphere, and (2) corpuscular radiation thought to introduce disturbances into the atmosphere in the polar regions which then travel equatorward. The tropospheric variations studied have two distinct time scales: (1) a few days, as little as one or two days, and (2) several weeks, the mean period of the atmospheric "index cycle" or lifespan of a whole anomalous "cycle" of the general circulation. These two time scales are, of course, to be added to still longer scales which have always attracted interest from the solar-terrestrial relations viewpoint.

At this time little can be said by way of evaluation of these efforts except that they are only in their beginning stages and that they should be pursued with full vigor. Solutions of many basic meteorological problems have not been found with the conventional approaches; while their poor showing does not rule out these approaches, meteorology needs to become more open-minded about alternate solutions. At present, the most serious shortcoming of the solar-terrestrial research effort is its purely statistical basis. We note a continuing lack of demonstrations of connecting mechanisms although some hypotheses have been advanced. One is also worried about the variety of time scales of atmospheric motion now studied for possible solar effects.

The writer believes that the subject may simplify considerably when the rapid evolution of solar measurements now taking place has led to sufficient refinement of the data and standardization into pertinent indices. Much evidence exists that solar as well as meteorological data used in research often have been too crude, partly because of necessity. The situation has lately improved and is continuing to improve regarding meteorological observations and their treatment. The writer, therefore, considers extension and consolidation of our new knowledge about the Sun as the most important step to be taken at this time.

Solar activities--The most active workers have been H. C. Willett and C. E. Palmer. Willett wants to trace certain solar influences through corpuscular radiation reaching the polar zones.

These may be responsible for rapid temperature changes as reported by Scherhag for the stratosphere over Germany. Palmer, on the other hand, has attributed sudden temperature rises in the equatorial stratosphere to solar flares. Such "impulsive generation of changes in the tropospheric circulation" may be the initiating mechanism for index trends propagating poleward from the equatorial zone. An unpublished study by Riehl of index trends over several years has indicated that poleward trends left the equatorial zone at about the proper time demanded by the hypothesis.

Jet stream--Within the last two years, direct study of jet streams by means of scientific exploration by aircraft has commenced in the United States. In the winter of 1952-53 some 20 flights were made with fighter aircraft under auspices of the U. S. Bureau of Aeronautics, Project AROWA, Norfolk, Va. Forecasts of the flights and routes to be flown were prepared at the University of Chicago. The final report on these flights was issued in March, 1954; the highest winds measured were near 250 knots over a ten-mile interval. In the winter of 1953-54 jet-stream flights have been made both by the Navy and the U. S. Air Force.

A summary report of the accumulated knowledge about the jet stream has been published by the Navy in their NAVAER series. This report was prepared at the University of Chicago by M. A. Alaka, C. L. Jordan, R. R. Renard, and H. Riehl.

Ross Gunn of the U. S. Weather Bureau communicates the statement of G. W. Brier relative to the activities at the Weather Bureau in solar weather research during the past year as follows: During the past year, Weather Bureau efforts in this field have been directed primarily towards an examination of the possible effect of short-term variations in solar activity (of the order of several days) on the sea-level pressure distribution. It is believed that such short-term effects offer the possibility of a better physical understanding of the basic solar-weather relationship than do the longer-term effects previously studied. To this end, a theoretical explanation of concurrent temperature (radiation) changes and pressure changes has been developed. The theory has been applied, with some indication of success, to the daily cyclic changes of temperature and pressure.

S. A. Korff of New York University, and Reporter on Cosmic Rays of the U. S. National Committee of the International Geophysical Year, has continued his studies and provides the Committee with the following summary of recent activities of his group: Investigation of cosmic-ray neutrons has continued. With the establishment of a cosmic-ray observing station on the summit of Mt. Wrangell in Alaska in the summer of 1953 at an altitude of 14,000 ft, it is planned to move the neutron monitor from sea level to the mountain station should it prove feasible to continue operations on Mt. Wrangell for a long period.

The group has completed a series of cosmic-ray neutron flights at the geomagnetic equator, in the region of the Galapagos Islands, geomagnetic latitude 9° N. These data will be compared with flights that we have obtained near the pole last summer.

A paper entitled Effects of the Cosmic Radiation on Terrestrial Isotope Distribution has appeared in the February, 1954, issue of the Transactions.

In the summer of 1954, in addition to continuing the neutron work in Alaska, it is planned to make more neutron flights in Minnesota, and to start construction of apparatus for the heavy primary determination.

A summary of plans for the International Geophysical Year, by S. A. Korff, has appeared in the March, 1954, issue of Physics Today.

During the year your Special Committee on Cosmic-Terrestrial Relationships has carried on active correspondence with numerous workers both in this country and abroad. By request a summary of three years' activity in the field of Solar-Terrestrial Relationships has been supplied to the Section of Terrestrial Magnetism and Electricity for inclusion in their report to the IUGG for the meeting in Rome in September, 1954.

The Committee is grateful for the excellent cooperation it has received and for the information that has been supplied from research agencies, both governmental and otherwise.

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SPECIAL ANNOUNCEMENTS

Changes of address--Attention is again called to the new policy of the Post Office Department under which undeliverable copies of our Transactions are returned at printed-matter mailing rates instead of second-class mailing rates as previously. The cost of postage on returned copies is considerable, and it is therefore again urged that all members take steps to advise the office of AGU promptly at times of change of address. At this particular time we are laying plans for the issuance of a new directory which will presumably be issued with the December number of the Transactions, and for this reason, also, we urge that you keep your address in our records up to date. Send word to the office of AGU at 1530 P Street, N. W., Washington 5, D. C.

National Register of Scientific and Technical Personnel--In November, 1953, we sent all members a copy of the questionnaire or form for the National Register of Scientific and Technical Personnel. The blank was to be filled in and returned in a stamped return envelope to the American Geological Institute, with which AGU is cooperating in this matter. We are advised by the Institute that although many of the returns have come in, some are still missing. If you have not returned yours, will you please do so without further delay. If you need a new form, drop a note to the office of AGU and this will be supplied.

Movement toward regionalization in the Pacific Northwest; meeting in Portland, Oregon, November 5, 1954--Upon the request of members in the unorganized Pacific Northwest Region, tentatively embracing Washington, Oregon, Idaho, Montana, Wyoming, Alaska, and adjoining Provinces of Canada, an ad hoc committee has been appointed consisting of C. C. McDonald, Chairman (U. S. Geological Survey, 207 Federal Building, Tacoma, Wash.), T. H. Campbell (Civil Engineering Department, University of Washington, Seattle 5, Wash.), Frank Neumann (Geology Department, University of Washington, Seattle 5, Wash.), and M. S. Sachs (2010 N. E. Thompson Street, Portland 12, Ore.). The meeting will be held November 5 at Portland. Nobert H. Leupold (P. O. Box 5082, Portland, Ore.) is Chairman of the Committee on Local Arrangements, and M. S. Sachs is Chairman of the Program Committee for Hydrology.

Meeting in Berkeley, California, February 4-5, 1955--Plans are developing for the Regional Meeting to be held at the University of California in Berkeley, February 4-5, 1955. J. W. Johnson (Professor of Engineering, University of California, Berkeley) has been named General Chairman and will be assisted by Ray K. Linsley (Professor of Civil Engineering, Stanford University, Stanford, Calif.) and David K. Todd (Professor of Civil Engineering, University of California, Berkeley) in developing the program and making local arrangements. Martin R. Huberty (Professor of Irrigation, University of California, Los Angeles) is Chairman of the Regional Committee, and R. Corday Counts, Jr., (U. S. Weather Bureau, Burlingame, Calif.) is Secretary. It appears that at least hydrology, meteorology, and oceanography will be involved in the program.

Thirty-Sixth Annual Meeting to be held in Washington, D. C., May 2-4, 1955--As initially announced in the June 1954 issue of the Transactions (p. 541), the Thirty-Sixth Annual Meeting will be held in Washington, D. C., May 2-4, 1955. This will serve to remind you of this first call for papers for the program and for suggestions in this regard. Watch Special Announcements in October and subsequently for further details.

Availability of reprints of Colloquium on Plastic Flow and Deformation within the Earth, and Symposium on the Interior of the Earth--A limited number of the reprints of the two above collections of papers and discussions are available at the schedule of prices set forth below. The Colloquium on Plastic Flow and Deformation Within the Earth was published in the August 1951 Transactions, pages 497-543, and is based on the papers presented at the meeting held in Hershey, Pennsylvania, in September, 1950. The Symposium on the Interior of the Earth was published in the February 1954 issue of the Transactions, pages 47-98, and is based on the papers and discussions of the Symposium presented at the Thirty-Fourth Annual Meeting of AGU in May, 1953. The schedule of prices is as follows. Colloquium or Symposium without covers: 0 to 9 copies, $1.00 each; 10 to 19 copies, $0.90 each; 20 to 29 copies, $0.80 each; 30 to 39 copies, $0.70 each; 40 or more, $0.60 each. The Colloquium is also available with paper covers. Add ten cents to the schedule given for those with covers.

Meeting of the AAAS in Berkeley, California, December 26-31, 1954--The 121st meeting of the American Association for the Advancement of Science will be held in Berkeley, December 26-31, 1954. The American Geophysical Union is now formally affiliated with the Association; and although it will not join with the AAAS in arranging a session of its own, preferring to hold its meeting at the usual time in late January, 1955, it is, however, the plan to co-sponsor symposia of geophysical interest and to aid in program planning. Suggestions in this regard should be sent to the office of AGU or to Chairman Martin R. Huberty of the Pacific Southwest Regional Committee.

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TRANSACTIONS
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PREDICTION OF THE PRESENT SUNSPOT CYCLE

A. G. McNish and J. V. Lincoln

In a recent paper [McNISH and LINCOLN, 1949], the writers presented a method for predicting smoothed annual sunspot numbers. This method was devised to assist in the prediction of maximum usable frequencies for radio communication, which are known to be closely correlated with the sunspot number.

The method consists of determining a "mean" sunspot cycle by forming averages of past observations for successive years after observed sunspot minima. Predictions are then made for each year by calculating the amount that the observed sunspot number for that year may be expected to exceed or fall short of the mean cycle for that epoch on the basis of the excess or deficiency exhibited by the sunspot number for the year in which the prediction was made. The prediction is calculated from a linear equation, using parameters selected to give the best prediction, in the sense of least squares, in respect to past data. Thus

$$R_n' = \overline{R_n} + k_{n-1}\,(R_{n-1} - \overline{R_{n-1}})$$

where R_i', $\overline{R_i}$, and R_i are the predicted, mean (that is, determined from the mean cycle) and observed values for the ith year after minimum, and k_i is the appropriate parameter derived in our previous paper.

Since the present sunspot cycle is approaching its end and a new cycle is about to begin, it is appropriate to examine the reliability of this method of prediction as applied to the present aging cycle. (The first spots of the new cycle, with reversed polarity, were observed in heliographic latitude 52° N on August 13, 1953, by Helen Dodson of the McMath-Hulbert Observatory, and confirmed by the Mount Wilson Observatory polarity measurements.) It should be remarked that the present cycle is outstanding among those that have been accurately observed. The first maximum of annual means, 151.8, centered on May, 1947, and the secondary maximum, 148.5, centered on October, 1948, are the highest values recorded since 1834, the date which the writers regard as the beginning of reliable quantitative sunspot observations [McNISH and LINCOLN, 1949]. Because of the unusually high sunspot numbers observed, the prediction method employed might be expected to produce poor results during the present cycle inasmuch as the method has a strong tendency to predict values which regress toward the mean.

Table 1--Observed and predicted annual values of current sunspot cycle centered on February

Item	Year									RMS[a]
	1945	1946	1947	1948	1949	1950	1951	1952	1953	
1	2	3	4	5	6	7	8	9	10	11
Observed	23.8	67.0	136.8	142.8	134.5	111.9	69.5	42.0	21.2	. . .
Predicted	18.2	71.1	104.5	125.3	111.9	103.6	83.8	50.7	29.6	. . .
Mean cycle	15.0	50.0	80.7	91.6	86.3	69.9	49.0	33.3	22.6	. . .
Observed - predicted	+5.6	- 4.1	+32.3	+17.5	+22.6	+ 8.3	-14.3	-8.7	-8.4	16.1
Observed - mean	+8.8	+17.0	+56.1	+51.2	+48.2	+42.0	+20.5	+8.7	-1.4	34.5
Expected (RMS) deviation of prediction	7.8	11.9	14.1	19.0	19.2	9.3	13.1	13.4	7.0	13.4

[a] Root-mean-square deviations.

The observed and predicted values for annual means, centered on February (February of 1944 was epoch of the minimum) for the years 1945 through 1953, together with various departures, are presented in Table 1. The predictions in the table are based on the final revised sunspot numbers, which differ somewhat from the preliminary estimates on which many of the predictions actually made at the time for calculation of radio frequencies were based. Row 4 of the table shows the departures of predicted values from those observed. Row 5 shows the extent to which the present cycle has been exceeding the mean cycle, deduced from the 11 cycles between 1834 and 1944. The estimated root-mean-square deviations for the present cycle computed from the formula

$$\sigma' = \sigma\left[1 + 1/N + (\Delta R_{n-1})^2 / \sum_{1}^{N} (\Delta R_{n-1})^2\right]^{1/2}$$

which takes into account errors in estimation of the parameters of the regression equation, are given in Row 6. The root-mean-square deviations for these three rows are shown in Column 11, which reveals that the method, in this case, has produced much better results than would have been obtained if "average" values had been predicted, and that errors in the predictions are approximately those anticipated in our earlier paper. The largest difference between observed and predicted values, 32.3, occurred in 1947. On the basis of the statistics developed for the prediction method, an error of this size for this year of the sunspot cycle is to be expected only about twice in a hundred cases.

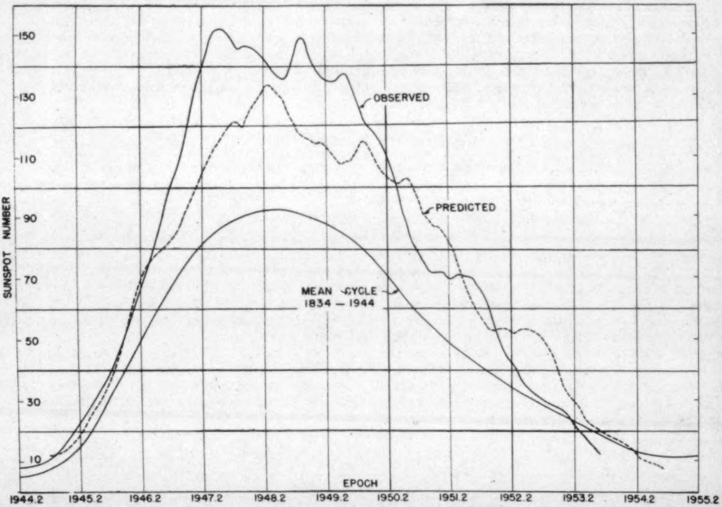

Fig. 1--Values of observed and predicted smoothed sunspot numbers compared with mean values

A graphical representation of the data, presented month by month rather than for successive years centered on February as in the first three rows of the table, is shown in Figure 1. These data were currently developed, month by month, for use in forecasting ionospheric frequencies, and consequently differ in some cases from the tabulated values.

Reference

McNISH, A. G., and J. V. LINCOLN, Prediction of sunspot numbers, Trans. Amer. Geophys. Union, v. 30, pp. 673-685, 1949.

National Bureau of Standards,
Washington 25, D. C.

(Communicated manuscript received February 19, 1954;
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Transactions, American Geophysical Union Volume 35, Number 5 October 1954

RAPID GEOMAGNETIC FLUCTUATIONS AT TUCSON, ARIZONA

E. J. Chernosky, E. Maple, and R. M. Coon

Abstract--Oscillatory fluctuations (micropulsations), appearing as trains of waves in the frequency range of 1/2 to 1/32 cps, were present about 20 pct of the time, with amplitudes of 0.01γ or more, in records of the vertical component of field made at Tucson with a large buried loop in the summer of 1947. The amplitudes of the oscillations were inversely proportional to their frequencies, and 1/20-cps oscillations occurred more often than those of other frequencies. The highest frequencies occurred at night and were related to times of large magnetic disturbance; the lowest frequencies occurred during the day at times of low or moderate activity, and the intermediate frequencies showed a transition of behavior. Random fluctuations, having no characteristic wave forms, had amplitudes which varied as the square root of the fluctuation duration. Average amplitudes of the three largest fluctuations per 15-min scaling interval decreased from 0.08γ at 60-sec duration to 0.01γ at one second; maximum amplitudes were about ten times these values. The random fluctuations also showed diurnal variations and a dependence on the degree of magnetic disturbance. A few audio-frequency measurements are also reported.

Introduction--Although the slow variations of the Earth's magnetic field have been the subject of extensive study for over a century, much less work has been done on fluctuations in the sub-audio- and audio-frequency ranges. The sub-audio-frequency range may be defined roughly as including fluctuations having durations or periods from about 10^2 to 10^{-1} sec. These fluctuations are, in general, too small and too rapid to be adequately studied on the magnetograms of the magnetic observatories. Fluctuations at frequencies above 15,000 cps have been studied by radio methods.

The geomagnetic fluctuations in the sub-audio range are of two types: (1) the 'random' fluctuations, which have no characteristic wave form but represent energy spread over a wide frequency band; and (2) the 'oscillatory' fluctuations which appear as trains of waves, each train representing energy in a rather narrow frequency band. Two fairly extensive studies have been made in recent years. VESTINE and his co-workers [1947, Chap. IX] have studied the random fluctuations having durations of ten seconds and more in the records made during the Polar Year 1932-1933, chiefly at high-latitude stations. HOLMBERG [1951] has studied the oscillatory fluctuations in the records made at Eskdalemuir in 1926-1927 with a large induction loop. Summaries of previous work are given in the above references and also in CHAPMAN and BARTELS [1940, Chap. X].

The present investigation is one of the few which have been made with adequate recording methods at the lower middle geomagnetic latitudes. The period of 12 days covered is rather short, but intensive analysis yields considerable information. The oscillatory fluctuations are considered in detail, and a briefer analysis of the random fluctuations is given. A few measurements at audio-frequencies are also reported.

Instrumentation--The measurements were made at the Tucson Observatory of the U. S. Coast and Geodetic Survey. The detector used was a large, buried horizontal loop having a sensitivity of 120 microvolts per gamma per cycle per second. The four-turn, 303-ft diameter, shielded loop had an effective flux area of 2.68×10^8 cm^2 and a d-c resistance of 9.2 ohms.

The loop output, after passing through a 60-cps reject filter, was amplified by a Perkin-Elmer breaker-type d-c amplifier. A General Electric recording fluxmeter integrated the voltage output of the amplifier and provided direct recording of fluctuations of magnetic field. A sensitivity of 0.01γ per division (1.9 mm) was used with a tape speed of 6 in/min (153 mm/min) which permitted resolution of fluctuations having a duration of one second (0.1 inch) or more.

A special pen-recentering device made it possible to record the larger fluctuations. When the recording pen reached the edge of the fluxmeter tape, it was quickly returned to the center of the tape whence the trace was continued. Each pen reset also introduced a small increment of d-c voltage opposing the signal so that long-period field changes or drift voltages were eventually compensated and the record freed from an unnecessary number of resets. A special tape feed permitted continuous recording for 12-hr periods.

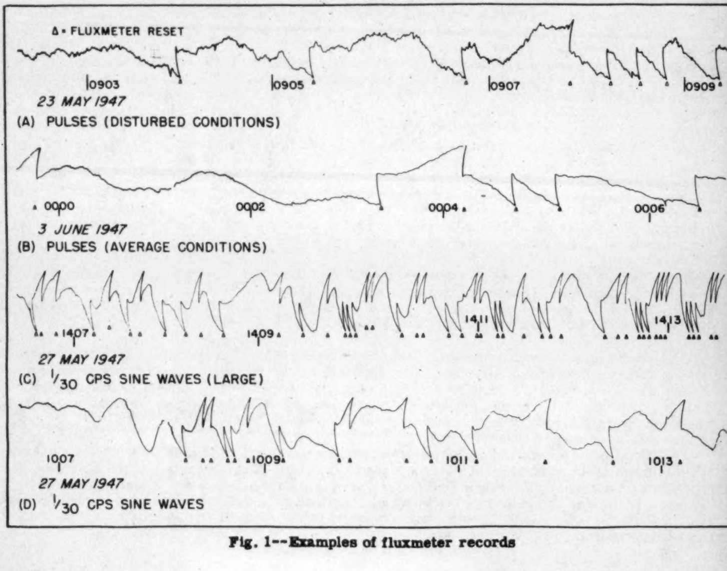
The overall response of the system was calibrated once a day. A known one-cps sinusoidal signal was introduced across a 0.1-ohm resistor in series with the loop, and the equivalent field change was calculated from the dimensions of the detector loop. The calibration method was checked by rotating a bar magnet, whose moment was accurately known, in a vertical plane at the center of the loop, and computing the field which linked the loop.

Reliability of records--Care was taken to insure that the signals recorded were of geomagnetic origin. The Tucson Observatory was relatively remote from populated areas. Artificial noises were eliminated as far as possible; those remaining, such as the fields of telephone-ringing currents, could usually be identified on the records.

Natural non-geomagnetic sources of noise, such as seismic deformation or tilting of the loop, were also considered. No correlation could be found with activity recorded on the Observatory seismographs or with wind velocity. Nulled-loop-turns tests showed that no appreciable false signals should be expected from changing earth currents or atmospheric potentials.

Only a few of the short-period field changes, such as the sudden commencements of magnetic storms, were large enough to appear distinctly on the Observatory's records. A check on the reliability of the smaller signals was afforded by measurements made with a temporary loop and battery-powered amplifier. This loop was located about 14 km from the buried loop and about twice as far from Tucson and the probable sources of artificial noise. Simultaneous recordings from the two systems showed the same fluctuations, with approximately the same magnitudes, at both locations, and indicated a distant origin, probably in the ionosphere.

Oscillatory fluctuations--Samples from the more than three km of fluxmeter tapes that were taken are shown in Figure 1. The major portion of the analysis is concerned with the oscillatory fluctuations (or simply oscillations) which appeared as trains of waves, each train lasting for three or more complete cycles. The records from May 22 to June 2, 1947, were evaluated in this analysis. Each 15-min interval recorded was scaled, a total of 869 intervals, representing 218 hours or 9.1 days of records obtained during the 12-day recording period.



(A) PULSES (DISTURBED CONDITIONS)

(B) PULSES (AVERAGE CONDITIONS)

(C) 1/30 CPS SINE WAVES (LARGE)

(D) 1/30 CPS SINE WAVES

Fig. 1--Examples of fluxmeter records

The oscillations chiefly considered were those having a constant period (± 10 pct) for three or more consecutive cycles and having amplitudes at least twice the amplitudes of any shorter-period fluctuations present. No appreciable oscillatory activity between one and 1/60 cps was observed outside the 1/2- to 1/32-cps frequency range. For analysis, the activity was divided into six frequency groups: 1/5 cps (1/2 to 1/7), 1/10 cps (1/8 to 1/12), 1/15 cps (1/13 to 1/17), 1/20 cps (1/18 to 1/22), 1/25 cps (1/23 to 1/27), and 1/30 cps (1/28 to 1/32). The period (to the nearest second), time of occurrence, and time length of each occurrence of these 'constant frequency' oscillations were recorded, and the peak-to-peak amplitude of the third largest cycle of oscillation in each 15-min interval was determined for each frequency group.

The occurrence of oscillatory activity of all frequencies is shown in Figure 2. In part A, spaces are assigned to each hour of each day included in the analysis. A black dot indicates activity sometime during the hour; an open circle indicates no oscillatory activity; no marking at all indicates that no records were available. Parts B and C show the per cent occurrence (that is, the per cent of total time scaled during which activity was in progress) for each local calendar day and clock hour, respectively (these curves do not come from part A, which does not indicate duration of activity). This presentation provides for ready recognition of periodic trends. The occurrence patterns of the different frequency groups are shown in Figures 3 and 4.

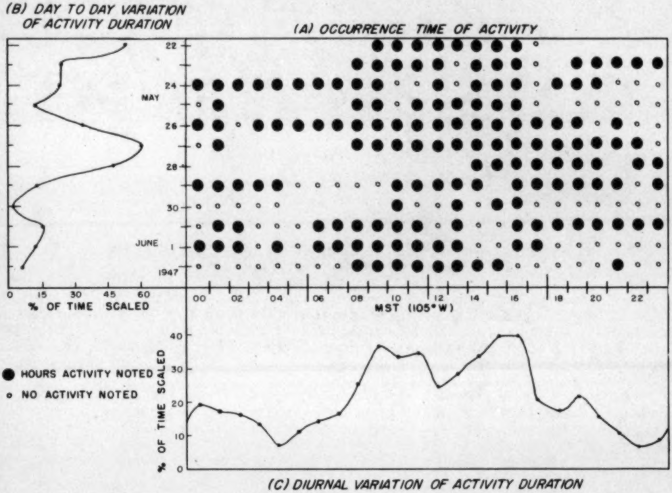


Fig. 2--Occurrence of 'constant-frequency' oscillations (all frequencies)

The average amplitudes of the oscillations are plotted against frequency in the upper curve of Figure 5, where the third largest cycle in each 15-min scaling interval has been taken (whether or not oscillations were found). The per cent occurrence of the oscillatory activity (lower curve of Figure 5) shows a sharp peak at 1/20 cps, while the two curves taken together indicate that the amplitudes of the oscillations observed were approximately inversely proportional of their frequencies.

A contour plot of per cent occurrence of the oscillations as a function of oscillation frequency and local clock hours is shown in Figure 6, while Figure 7 is a similar plot of relative amplitudes; the data have been smoothed along the clock-hours coordinate for plotting purposes. The oscillations having frequencies between 1/13 and 1/32 cps occurred more often, and with larger amplitudes, in the daylight hours than at night, while the 1/2- to 1/12-cps oscillations appeared chiefly during the night hours.

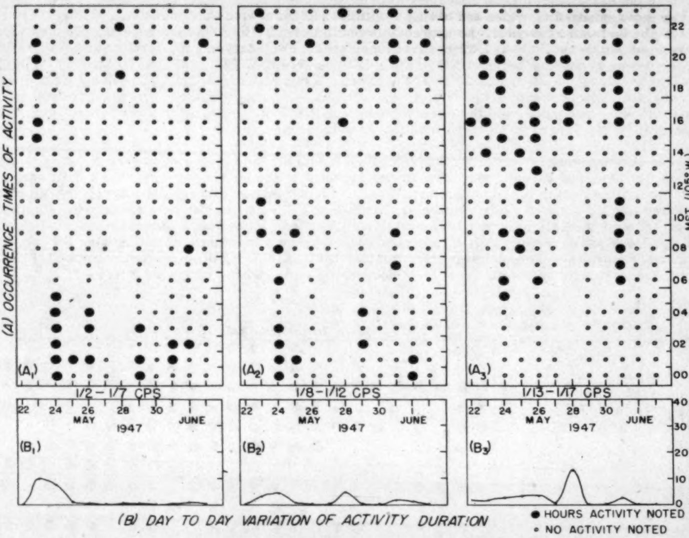


Fig. 3--Occurrence of 'constant-frequency' oscillations by frequency groups (1/5, 1/10, and 1/15 cps)

The K index from the Tucson Magnetic Observatory ranged from 0 through 7 and averaged 2.9 for all the scaling intervals used for the oscillatory fluctuations. In Table 1 the average amplitudes of the oscillations are shown for those intervals for which the K index was 0 or 1, 2 or 3, 4 or 5, and 6 or 7. Average amplitudes are shown for all intervals having the K indices indicated and also for only those intervals which had oscillatory activity of the frequency group shown.

At the highest frequencies observed (1/2 to 1/12 cps) the amplitudes increased sharply with increasing K index, while at the lowest frequencies (1/28 to 1/32 cps) the largest amplitudes occurred for K values of 2 and 3. The intermediate frequencies (1/13 to 1/27 cps) showed a gradual transition in their behavior. On the one day which was very quiet magnetically (May 30, average K = 1.2) practically no oscillatory activity occurred. An average K of 2.4 was computed for all intervals having no oscillatory activity.

Relatively pure sinusoidal wave forms sometimes occurred, and these were examined as a subgroup of constant-frequency oscillations, the criteria being durations of five or more cycles and amplitudes at least ten times those of any higher frequencies present. The intervals in which this 'sine-wave' activity occurred were mostly in daylight hours, as indicated in Figure 8, and had an average K of 3.4. These oscillations, containing energy in a narrower frequency band than did the others, were probably not basically different; some variation of band-width would be expected in such phenomena, and lack of other fluctuations occurring simultaneously would make the oscillations appear more 'pure.'

Oscillatory fluctuations of variable frequency, that is, wave trains having different periods for successive cycles, were also observed. These fluctuations appeared at random times and showed no particular pattern of amplitude variation. Their occurrence intervals had an average K of 3.6.

Table 1--Variation of average amplitudes of oscillatory activity with K index for Tucson, 1947

(All amplitudes in units of 0.01γ)

Frequency	Item[a]	K index				
		0,1	2,3	4,5	6,7	0-7
cps						
1/5 (1/2 - 1/7)	All	0	0.1	0.4	4.4	0.3
	Active	. . .	3.3	5.6	10.3	6.3
	Occurrence ratio	0	0.6	1.3	7.5	1.0
1/10 (1/8 to 1/12)	All	0	0.1	0.3	6.3	0.4
	Active	. . .	3.8	4.0	15.7	8.0
	Occurrence ratio	0	0.5	1.5	14.0	1.0
1/15 (1/13 - 1/17)	All	0	1.0	1.7	0.7	1.0
	Active	. . .	12.9	17.1	25.0	14.7
	Occurrence ratio	0	1.1	1.5	0.5	1.0
1/20 (1/18 - 1/22)	All	0.5	1.8	5.1	0	2.4
	Active	11.8	11.3	27.4	. . .	16.9
	Occurrence ratio	0.3	1.1	1.3	0	1.0
1/25 (1/23 - 1/27)	All	0.3	2.4	2.0	0	1.9
	Active	5.3	17.4	38.7	. . .	19.4
	Occurrence ratio	0.5	1.4	0.5	0	1.0
1/30 (1/28 - 1/32)	All	0.4	4.0	0.2	0	2.3
	Active	7.0	40.1	12.3	. . .	34.7
	Occurrence ratio	0.8	1.3	0.2	0	1.0

[a] All and active imply all or only the active intervals. Occurrence ratio is the number of active intervals divided by number of intervals expected to be active on the assumption that the activity is independent of K index.

Random fluctuations--The random fluctuations are defined as those which produce recognizable departures from, and subsequent returns to, a 'normal' field value, but which exhibit no characteristic wave form. The duration of the fluctuation is defined as the interval between the departure from and the return to the 'normal' field value; the amplitude is taken as the maximum excursion from the 'normal' value.

The analysis of the random fluctuations was less intensive than that of the oscillations. In the 1947 records, the first 15-min interval of every third hour of alternate days from May 22 to June 10 (61 intervals in all) was selected for evaluation. The scaling intervals were well distributed over the local clock hours. A few records obtained in June, 1948, were also scaled for random fluctuations. The 1948 data were irregularly spaced over the local clock hours and are not included in the graphs presented here; the results, however, confirm the trends found in the 1947 data.

The fluctuation durations chosen for analysis were 1, 2, 6, 15, and 60 sec, and the amplitudes of the first, second, and third largest fluctuations of each duration in each scaling interval were recorded. Durations of from 85 to 125 pct of the nominal durations were included, that is, the 15-sec fluctuations included those whose durations were between 12.7 and 18.8 sec.

The mean amplitudes of the three largest fluctuations from each scaling interval (circled points) are plotted against fluctuation duration in the upper curve of Figure 9. The mean amplitudes of the largest and of the third largest fluctuation from each scaling interval are shown at the top and bottom of the vertical line. The three largest fluctuations of each duration which were observed in any of the 61 scaling intervals are shown in the lower curve of Figure 9.

Both the mean and the maximum amplitudes of the random fluctuations increased approximately as the square root of the duration. The three largest fluctuations follow quite closely the best-fitting line whose slope is 0.60. For the average amplitudes, the slope of the line fitted to the circled points only is 0.51.

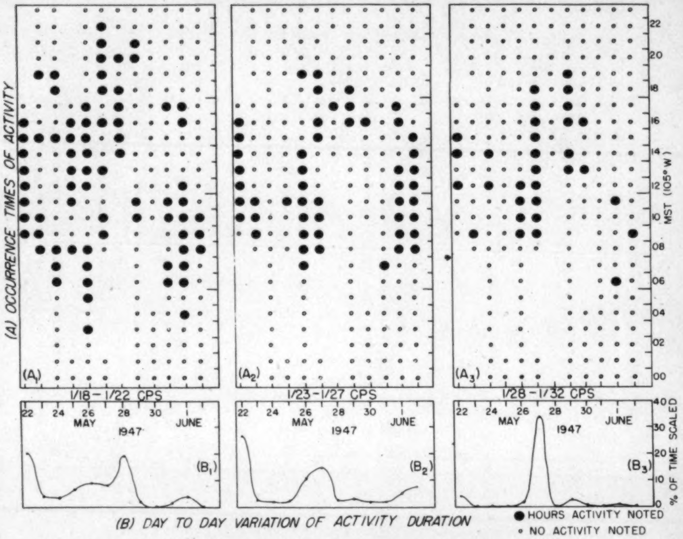


Fig. 4--Occurrence of 'constant-frequency' oscillations by frequency groups (1/20, 1/25, and 1/30 cps)

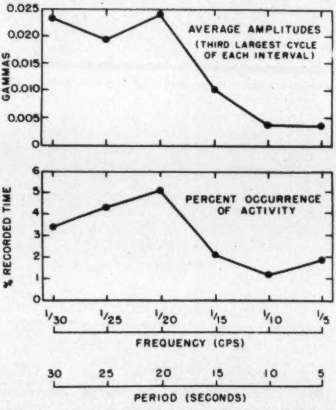


Fig. 5--Variation of oscillatory activity with frequency

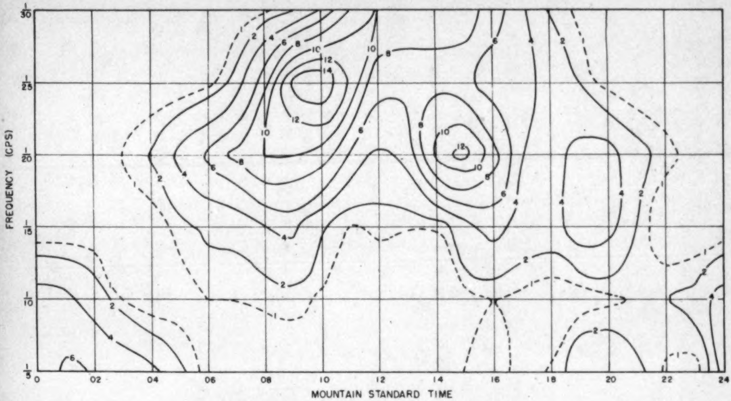


Fig. 6--Percentage occurrence of oscillatory activity as a function of frequency and local clock hours

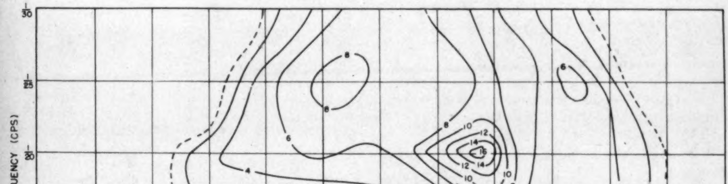


Fig. 7--Average amplitudes of oscillatory activity as a function of frequency and local clock hours (contours in relative values)

Of interest is the positive deviation of the 15-sec fluctuations from the general trend. It is much more pronounced for the mean amplitudes than for the maximum values, indicating that the deviation is in the frequency of occurrence of the 15-sec fluctuations rather than in the amplitudes of the individual fluctuations. A repetition of this peak in the 1948 data (not shown here) indicates that 15 sec is probably the most frequently occurring duration for fluctuations at the Tucson geomagnetic latitude of +40°, in the summer months if not throughout the year.

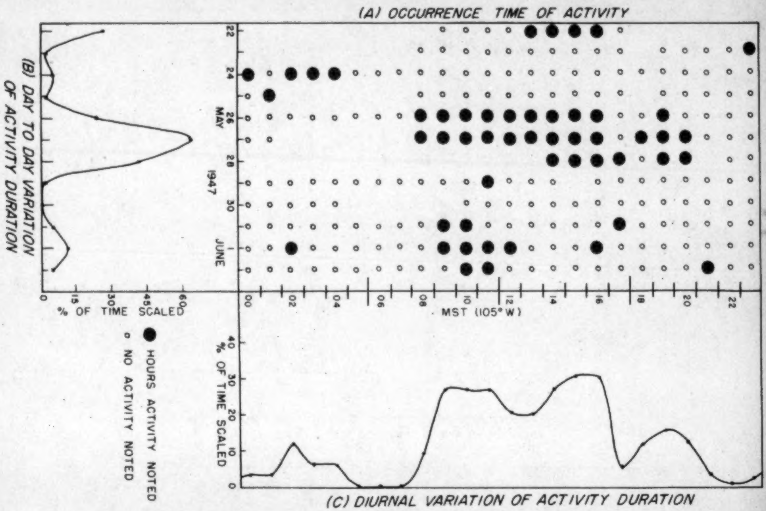


Fig. 8--Occurrence of 'sine-wave' oscillatory activity

The 60-sec fluctuations were relatively infrequent; they were found in 75 pct of the intervals scaled, with 50 pct of the intervals having more than one fluctuation each. For the other durations, 90 pct or more of the intervals had one fluctuation and 70 pct or more had more than one fluctuation.

The largest amplitudes shown for the random fluctuations would have been increased by a factor of two or three if all available records had been scaled. The largest oscillation scaled was 1.1γ peak-to-peak at 1/30 cps, which is comparable to the largest random fluctuations. The relative infrequency of occurrence of the oscillations brings their average amplitudes down well below those of the random fluctuations.

The mean amplitudes of the three largest fluctuations per scaling interval are plotted against local clock hours in Figure 10. Not more than eight intervals were available for each clock hour shown, and these curves are less reliable than those for the oscillatory fluctuations. The 60-sec and six-sec fluctuations were largest during the night, while the 15-sec fluctuations were largest during the day. The two- and one-sec fluctuations increased slightly in amplitude during the afternoon and evening hours.

The amplitudes of the random fluctuations tended to increase with the Tucson K index. This effect was most pronounced for the 60- and six-sec fluctuations, while very little correlation was observed between the K index and the two- and one-sec fluctuations. The basis for this comparison is not too good, since the K index indicates the maximum disturbance during a three-hour interval, while only 15 minutes of the three hours were scaled for the fluctuations. For the longer durations it was also observed that the amplitude decrease factor (ratio of the average of the three largest fluctuations to the difference between the first and third largest in the interval) increased for large values of K, indicating a more sustained level of activity.

Comparison with previous results--The most extensive recent study of oscillatory geomagnetic fluctuations is that of HOLMBERG [1951], who analyzed oscillations having frequencies of from 1/5 to 1/20 cps in the 1926-1927 records from Eskdalemuir. He, as well as others previously, found

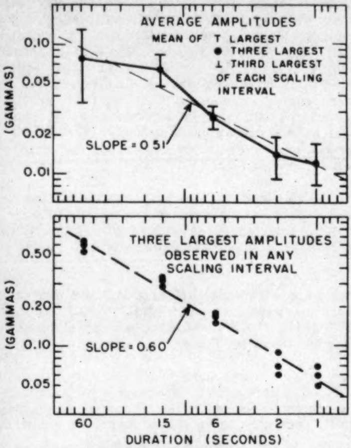


Fig. 9--Random fluctuations; variation of amplitude with duration

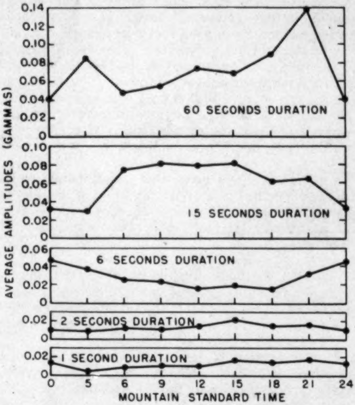


Fig. 10--Random fluctuations; diurnal variations

that oscillations having frequencies of about 1/10 cps and higher were associated with times of large magnetic disturbance, in agreement with the Tucson data. These oscillations were near the limit of time resolution of the Eskdalemuir records and were not analyzed further.

In the frequency range from 1/15 to 1/60 cps, the Eskdalemuir results for the summer solstice agree rather well with the Tucson data in that most of the oscillations are centered in a band around 20 seconds and lie between 1/15 and 1/32 cps. At both stations the amplitudes of the oscillations increased with their periods; the amplitudes found at Tucson are somewhat larger than those reported for Eskdalemuir. Several occurrences of oscillations between 1/32 and 1/60 cps were observed at Eskdalemuir, however, but not at Tucson; a few oscillations of small amplitude in this frequency range might have been missed because of the selection rules used in scaling the Tucson records.

No correlation was found between the Eskdalemuir oscillations at frequencies below 1/15 cps and the general level of magnetic disturbance. This may have been caused by the use of magnetic character figures or ranges of the elements which were characteristic of the day as a whole, rather than the three-hour K index, for the comparison. JOHNSTON [1937] observed that in the 1933 Watheroo records, oscillations of 20- to 30-sec period were more closely related to magnetic disturbance than were the slower oscillations of 30- to 80-sec period.

The most extensive analysis of the random geomagnetic fluctuations in the sub-audio-frequency range is included in the comprehensive work by VESTINE, LANGE, LAPORTE, and SCOTT [1947, Chap. IX]. They studied fluctuations having durations of from ten seconds to ten hours with chief emphasis on durations of five minutes or less. They noted that the fluctuations having longer durations also had greater amplitudes, but did not reduce this to a quantitative relationship. Their study was concerned more with the frequency of occurrence of the various fluctuations. They concluded that fluctuations having durations of about 50 seconds occurred more frequently than those of other durations. This conclusion was based chiefly on data from high-latitude stations; at the latitude of Tucson, a maximum frequency of occurrence at about 15 seconds is indicated by the present data.

Vestine noted that fluctuations of large amplitude occur more frequently at times of magnetic disturbance, in agreement with the present data. Neither study was best designed to reveal the degree of correlation which exists between the sub-audio random fluctuations and the K index.

Audio-frequency fluctuations--A few measurements of fluctuations in the audio-frequency range were made; the results are presented here because of the very limited information previously published in this frequency range. The signal from the detector loop was fed into a Hewlett-Packard wave analyzer whose output was recorded on a Brush magnetic pen recorder. The signals appeared as 'bursts' of activity which, after rectification, gave pulses of 0.01- to 0.02-sec duration. Pulses with amplitudes greater than half-scale were counted in each ten-sec interval, and the records showed a rather uniform number of pulses at the frequencies measured (500, 1000, 2000, 4000, 8000, 12,000, and 16,000 cps) with a small peak at 8000 cps. (Similar measurements using a horizontal straight-wire antenna as the detector showed a more marked peak at 8000 cps.) The sensitivity of the detector loop was 120 microvolts per gamma per cycle per second, and full scale on the recorder represented about 500 microvolts induced in the loop.

The results indicate that, for the band width of 290 cps used, the average amplitude of the observed 'bursts' of activity was somewhat less than $4 \times 10^{-3}\gamma$ at 500 cps and was approximately inversely proportional to frequency up to 16,000 cps. These fluctuations were probably caused by atmospherics (distant thunderstorm activity). The data were taken during a magnetically quiet period.

WILLIS [1948], in Scotland, found that the fluctuations in the range of five to 1000 cps decreased roughly as the 3/2 power of the frequency. For a one-cps pass band and a detector with a two- to three-sec time constant, Willis obtained a value of $7 \times 10^{-6}\gamma$ at 400 cps for the horizontal component, and fluctuations in the vertical component were even smaller there.

The values obtained at Tucson are more than an order of magnitude larger than those from Scotland after correction for the measurement band widths used. This difference is at least partially accounted for by the comparatively long-time constant used by Willis. It may also be caused in part by the greater amount of thunderstorm activity occurring in the United States as compared with Great Britain and Europe.

Conclusions--The data presented here are limited in amount, and, since all of them were taken during the summer months, they may not be representative of the entire year. Intensive analysis of the records, and the high sensitivity and recording tape speed used, have, however, yielded considerable information on the sub-audio-frequency fluctuations.

Oscillatory fluctuations (micropulsations) in the vertical component of the geomagnetic field, appearing as trains of waves with frequencies of 1/2 to 1/32 cps and amplitudes of 0.01γ or more, were present in the Tucson records during approximately 20 pct of the time. Their amplitudes were inversely proportional to their frequencies.

The highest-frequency oscillations observed (1/2 to 1/12 cps) appeared chiefly at night, and their amplitudes increased rapidly with increasing K index. The lowest frequencies (1/28 to 1/32 cps) appeared around midday, in general coincidence with the hours having the maximum height separation of the F1 and F2 ionospheric layers; they appeared more frequently, and with larger amplitudes, with K indices of 2 and 3. The intermediate frequencies (1/13 to 1/27 cps) occurred most frequently during daylight and early evening hours; their amplitudes increased moderately with increasing K index.

The analysis of the random fluctuations was less intensive, and the results are less conclusive. Their amplitudes at Tucson increased as the square root of the fluctuation duration in the one- to 60-sec range. The average amplitudes of the three largest fluctuations per 15-min interval decreased from 0.08γ at 60-sec to 0.01γ at one-sec duration. The largest fluctuations found in the records scaled were about ten times these average values. Random fluctuations of 15-sec duration occurred more frequently than the other durations studied, while the 60-sec fluctuations occurred least frequently.

The amplitudes of the fluctuations observed at Tucson may not be representative for this latitude. The ranges in Z for various values of the K index are much less than the corresponding ranges of H and D on the Observatory magnetograms [BARTELS, HECK, and JOHNSTON, 1939], and it seems likely that the fluctuations of Z in the one- to 60-sec range would also be comparatively small.

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The cooperation of the U. S. Coast and Geodetic Survey in making available the facilities of the Tucson Magnetic Observatory is appreciated, and thanks are expressed to J. H. Nelson and his staff at the Observatory for the considerable assistance given in many ways.

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VAPOR PRESSURE OF SEA-SALT SOLUTIONS

A. B. Arons and C. F. Kientzler

(Contribution No. 635 from the Woods Hole Oceanographic Institution)

Abstract--Vapor pressures of sea-salt solutions at temperatures between freezing and 25°C are reported and are tied in with previously reported measurements of Higashi made at temperatures between 25 and 175°C.

Introduction--Although HIGASHI and Others [1931] have published measurements of vapor pressure of sea-salt solutions, these were obtained at temperatures from 25 to 175°C, and no direct experimental values have been available for temperatures between freezing and 25°C.

Recent work on atmospheric sea-salt nuclei [WOODCOCK and GIFFORD, 1949], as well as studies of sea fogs and of clouds in which temperatures are above freezing, requires accurate knowledge of vapor pressure in the lower temperature range; and an experimental program of vapor-pressure measurement was consequently undertaken.

Apparatus and preparation of samples--The experimental technique used was a modification of that reported by GIBSON and ADAMS [1933]. A schematic diagram is shown in Figure 1, and a

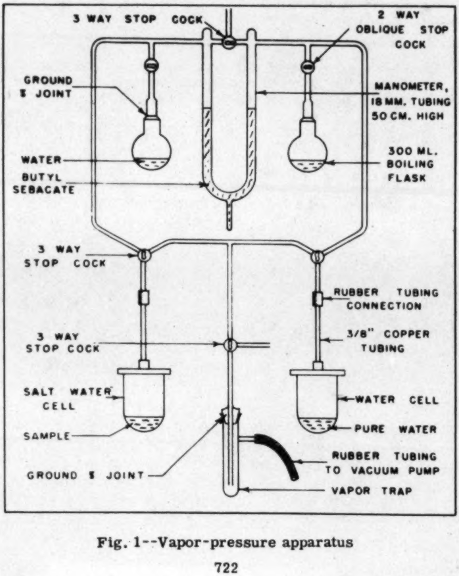
3 WAY STOP COCK
2 WAY OBLIQUE STOP COCK
GROUND ₮ JOINT
MANOMETER, 18 MM. TUBING 50 CM. HIGH
WATER
BUTYL SEBACATE
300 ML. BOILING FLASK
3 WAY STOP COCK
RUBBER TUBING CONNECTION
3 WAY STOP COCK
3/8" COPPER TUBING
SALT WATER CELL
WATER CELL
SAMPLE
PURE WATER
RUBBER TUBING TO VACUUM PUMP
GROUND ₮ JOINT
VAPOR TRAP

Fig. 1--Vapor-pressure apparatus

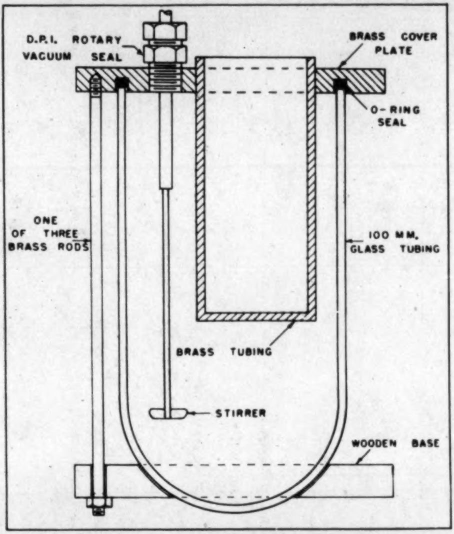

Fig. 2--Section view of test cell

sketch of the specially designed test cells is shown in Figure 2. Samples were degassed by successive sublimation in the test cells. Vapor pressure of a salt-solution sample in one cell was compared with the vapor pressure of pure water in the second cell by means of the differential manometer containing butyl sebacate. Manometer heights were read by means of a cathetometer. The test cells were accurately thermostated in a common bath. Short blasts of vapor from previously degassed water in the 300-ml boiling flasks were used to hasten the attainment of vapor-pressure equilibrium in the system when measurement was begun. For temperatures below 0° C (the freezing point of the pure water in the comparison flask), correction was made for the difference between the vapor pressures of ice and of super-cooled water.

Solution samples of varying concentration up to saturation ($Cl \approx 155$ ⁰/oo) were obtained by evaporation of ordinary sea water at temperatures of about 80° C. Some precipitate ($CaCO_3$) appeared when the chlorinity exceeded 40 ⁰/oo and was followed by $CaSO_4 \cdot 2H_2O$ at concentrations above 70 ⁰/oo [THOMPSON and ROBINSON, 1932].

Samples for vapor-pressure measurement were decanted at room temperature. Concentration was determined by silver nitrate titration, and Higashi's values of density of concentrated sea-salt solutions were used in the calculation of chlorinity.

Several careful checks indicated that successive degassing of the sample did not cause sufficient loss of water to affect the concentration appreciably.

Experimental values of vapor-pressure lowering--The original experimental points are shown plotted in Figure 3 as vapor-pressure lowering ($p_0 - p$) versus reciprocal absolute temperature (1/T) for the various concentration samples used. Smooth curves were drawn through these points. A cross-plot ($p_0 - p$ versus log chlorinity for various temperatures) was then made from the curves of Figure 3, and smooth curves were again drawn. Final curves of $p_0 - p$ versus 1/T for various integral values of chlorinity were obtained by reading suitable values from the cross-plot and are shown in Figure 4. The smoothed numerical values used in plotting Figure 4 are given in Table 1.

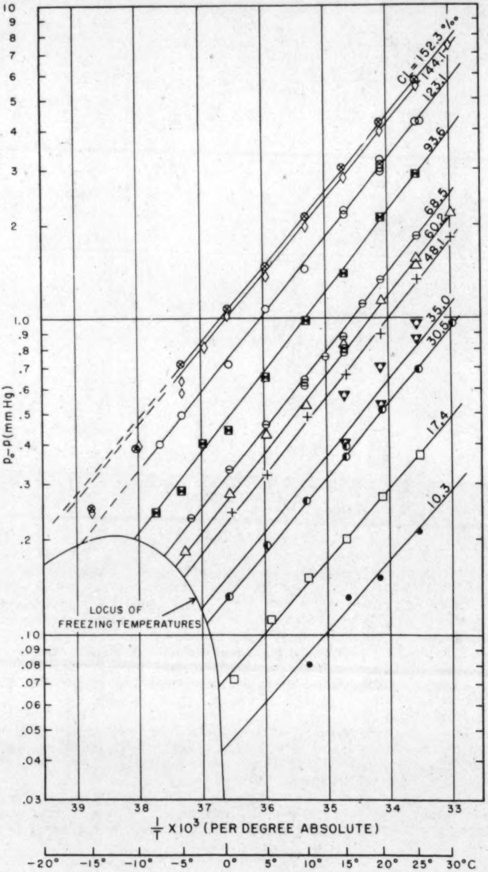

Fig. 3--Relationship of vapor-pressure lowering, $p_o - p$, for various sea-water solutions to reciprocal temperature (original experimental results)

Before the techniques of degassing and insuring pressure equilibrium in the system were perfected, runs on some of the early samples showed a very large scatter (as, for example, the Cl = 35 ^{o}/oo points in Fig. 3). All experimental points have been included in Figure 3 for the sake of completeness, but principal weight in smoothing and in determining the slopes of the curves has been given to the later, more reproducible measurements.

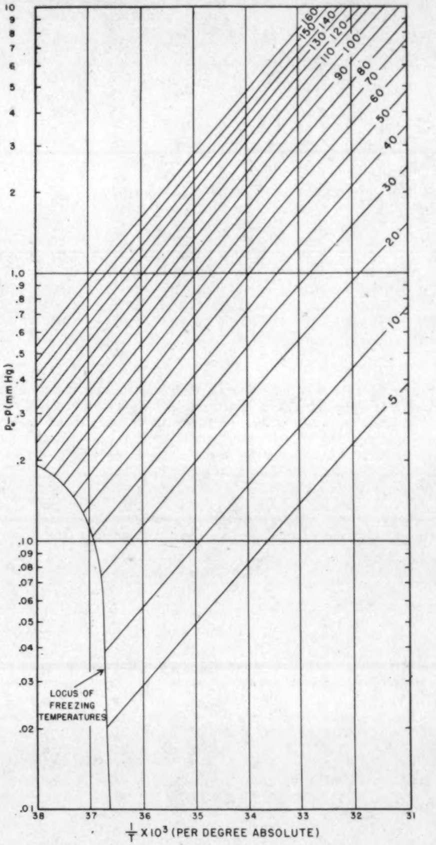

Fig. 4--Relationship of vapor-pressure lowering, $p_o - p$, for various chlorinities to reciprocal temperature (smoothed original values)

Because of the inaccessibility of Higashi's vapor-pressure data in the original publication, it was deemed desirable to rework his data and tie them in with the results of this investigation, thus supplying a complete summary of vapor pressure of sea-salt solutions all the way from freezing to 175° C.

Table 1--Values of vapor-pressure lowering, in millimeters of mercury, used in Figure 4 (results of this investigation)

Chlorinity	Temperature °C									
	35	30	25	20	15	10	5	0	-5	-10
^{o}/oo										
5	0.18	0.13	0.10	0.08	0.06	0.04	0.03	0.02	...	...
10	0.35	0.27	0.20	0.15	0.11	0.08	0.06	0.04	...	...
20	0.74	0.56	0.43	0.32	0.23	0.16	0.12	0.08	...	...
30	1.20	0.90	0.68	0.49	0.36	0.26	0.18	0.12	...	...
40	1.67	1.25	0.92	0.67	0.49	0.35	0.24	0.17	...	...
50	2.24	1.67	1.24	0.90	0.65	0.45	0.31	0.22	0.15	...
60	2.87	2.14	1.58	1.14	0.81	0.57	0.39	0.27	0.18	...
70	3.45	2.57	1.88	1.36	0.96	0.68	0.47	0.32	0.22	...
80	4.08	3.04	2.25	1.62	1.16	0.81	0.56	0.38	0.26	...
90	4.87	3.65	2.67	1.92	1.37	0.95	0.66	0.44	0.30	0.20
100	5.64	4.17	3.07	2.20	1.57	1.10	0.76	0.52	0.35	0.23
110	6.50	4.81	3.52	2.55	1.82	1.27	0.87	0.59	0.40	0.27
120	7.29	5.44	4.03	2.91	2.07	1.44	1.00	0.68	0.46	0.31
130	8.17	6.09	4.50	3.28	2.36	1.67	1.16	0.79	0.54	0.36
140	8.89	6.71	4.99	3.63	2.62	1.85	1.28	0.88	0.60	0.41
150	9.93	7.42	5.52	4.01	2.93	2.08	1.47	1.02	0.69	0.46
160	10.73	8.20	6.14	4.49	3.27	2.33	1.65	1.14	0.79	0.53

In re-examining Higashi's smoothed values and original experimental results, various large discrepancies were noted, and his 25°C measurements (which influenced the manner in which he drew his curves in the lower part of his temperature range) were found to show exceedingly large scatter. It was therefore decided to re-smooth Higashi's data, substituting our 25°C results for his. The data were plotted and cross-plotted in the same manner as that described above, and the final, smoothed curves for the entire temperature range from freezing to 175°C are shown in Figure 5. The values used to plot Figure 5 are given in Table 2.

Table 2--Values of vapor-pressure lowering, in millimeters of mercury, used in Figure 5 (re-smoothed results of Higashi)

Chlorinity	Temperature °C							
	175	150	125	100	75	50	25	0
^{o}/oo								
10	33.0	18.5	9.7	4.75	1.99	0.74	0.20	0.04
20	72.6	41.0	21.1	10.2	4.40	1.54	0.43	0.08
30	118	65.8	34.0	16.4	7.08	2.50	0.68	0.12
40	168	94.5	49.3	23.9	9.99	3.58	0.92	0.17
50	227	128	66.5	32.1	13.2	4.75	1.24	0.22
60	298	168	86.2	41.0	16.6	5.96	1.58	0.27
70	374	213	108	52.0	21.1	7.41	1.88	0.32
80	457	257	132	62.2	25.1	8.85	2.25	0.38
90	551	308	157	74.7	30.1	10.3	2.67	0.44
100	640	363	184	87.4	34.8	11.7	3.07	0.52
110	749	425	217	103	41.1	13.6	3.52	0.59
120	868	486	248	117	46.3	15.2	4.03	0.68
130	1000	568	287	135	53.7	17.2	4.50	0.79
140	1115	630	317	151	58.4	18.8	4.99	0.88
150	1260	722	365	170	65.4	20.9	5.52	1.02
160	1440	822	408	188	72.8	22.8	6.14	1.14

WITTING [1908] gives a relation between vapor pressure and concentration of sea-salt solutions. This relation, based on thermodynamic equations and experimental freezing-point lowerings, should be valid for dilute solutions. The dashed curves in Figure 5 show Witting's equation to be in reasonably good agreement with our results at chlorinities of 10 and 20 ^{o}/oo.

In view of the smoothing processes used in obtaining the final values of vapor-pressure lowering, it is difficult to make an objective estimate of the accuracy of the results, but the authors feel this to be of the order of two per cent.

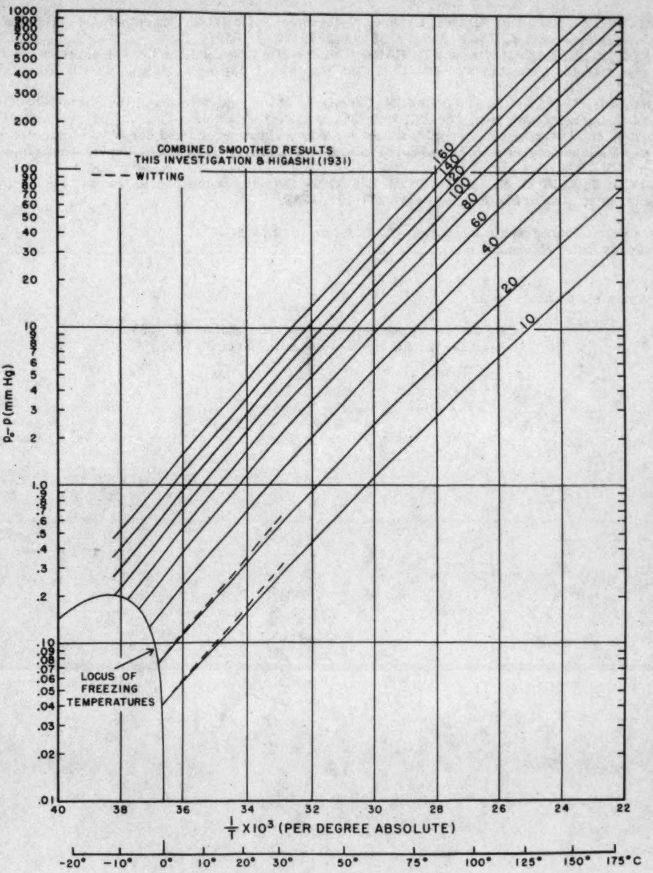

Fig. 5--Relationship of vapor-pressure lowering, $p_o - p$, for various chlorinities to reciprocal temperature

Acknowledgment--The authors wish to thank Charles Keith and Alfred Woodcock for their continued interest and helpful advice on various experimental problems. The work was performed under a contract with the Office of Naval Research.

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A NOTE ON THE REFLECTION OF DIFFUSE RADIATION BY THE SEA SURFACE

Morris Neiburger

(University of California, Los Angeles, Calif., Department of Meteorology, Contribution No. 24)

Abstract--The measurements of the fraction returning upward of the downward radiation at various levels below stratus cloud, which were presented by the author in 1948, gave larger values than 0.066, the theoretical value for the reflectivity of a plane water surface. By fitting a regression curve to the data at various elevations, it is shown that the effect of haze below the point of observation can explain only part of the difference, and that the average fraction returning upward at the sea surface is probably 0.095. Powell and Clarke's measurements show that scattering by bubbles and particulate matter is probably sufficient to account for the difference between this value and the theoretical value. The particle-size distribution required to give the observed variation of albedo with height is computed and shown to be consistent with the expected distribution above the sea surface.

The explanation I proposed [NEIBURGER, 1948] for the discrepancy between the measured values of the reflectivity of the sea surface for insolation coming through a stratus overcast and Schmidt's theoretical value of the albedo for isotropic diffuse radiation is invalid in the light of the discovery by BURT [1953] that Schmidt made an error in his computation. The corrected theoretical value, 0.066, is identical to that for direct radiation with solar altitude approximately 28.5°, so that lack of isotropy would appear to explain an increase above 0.066 only for solar altitudes smaller than this. Since practically all the measurements below the coastal stratus were made with higher Sun, the average value of 0.105 requires some other explanation. On the basis of the discussion in my paper of the sources of error, it does not seem likely that the measurements are greatly in error. Burt's own measurements over Chesapeake Bay give an average value almost as high (0.094).

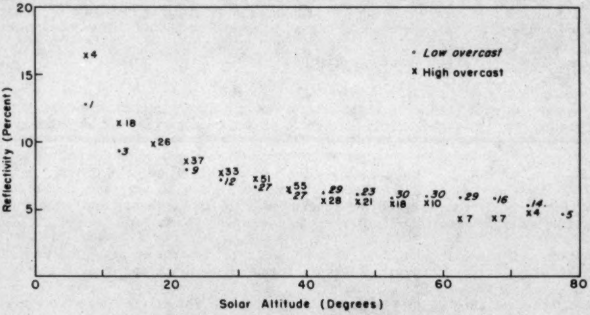

Fig. 1--Reflection of radiation coming through overcast by Lake Hefner, Oklahoma [ANDERSON, 1953]

The largest available series of measurements of albedo of a water surface is that of ANDERSON [1953]. His data, obtained over Lake Hefner, Oklahoma, include 242 measurements below low overcast clouds, and 328 below high overcast clouds. His values are presented in the form of graphs which show the variation with solar elevation. Figure 1 is taken from Figures 11 and 12 of his thesis. Below both high and low overcast there is variation with solar altitude which indicates that the radiation is not isotropic. For low overcast Anderson's data give albedos greater than 0.066 when the solar altitude less than 32.5°, in close agreement with the theoretical result; for high overcast the 0.066 value is reached at about 35°, with somewhat lower albedos than for low overcast at higher Sun, and somewhat higher albedos than for low overcast at lower solar altitudes. The Lake Hefner data show that the radiation through overcast is anisotropic, with the departure from isotropy greater for high than for low overcast. The values for overcast skies are in general consistent with the Fresnel theory of reflection.

The explanation of the high values measured off the California Coast and over Chesapeake Bay must be sought in factors which were different for these observations than for those over Lake Hefner. The instruments used were the same, namely, Eppley pyrheliometers. The main factor common to the California and Chesapeake observations and different from the Lake Hefner observations is that the former were over salt water, and the latter over fresh. The index of refraction of sea water is not significantly different from that of fresh water, so the optical behavior at the surface itself may be expected to be the same. No significant correlation was reported between wind speed, or character of water surface, and albedo both for the ocean (and Bay) and for the lake, so that the character of the waves probably played an insignificant role. (Walter Munk has shown in an unpublished computation that the effect of roughening of the surface is to decrease the albedo slightly.) The factors which may be responsible are scattering by salt haze above the sea surface and by bubbles and particulate matter below it. It is of interest to see to what extent each of these factors contributes to explaining the discrepancy.

The possibility that scattering by haze influenced the measurements was mentioned in my paper, but not considered important. The reason was that the blimp observations had been tabulated as a function of height above the sea surface, and, except at the lowest elevation (100 ft), no systematic variation with height was observed. The average value at 100 ft was 0.085 with standard deviation 0.025; at all other levels for which more than two measurements were made the average ranged between 0.083 and 0.151 with standard deviations which were generally around 0.05, and always sufficient to allow the interpretation that the true average for all levels might be close to the mean of 0.105.

To examine more carefully the amount the observations were influenced by haze, regression curves were fitted to them. When all the data were used the previous hypothesis appeared to be confirmed: The line of best fit indicated negligible variation with height. However, since the observations at higher levels could be made only when the stratus was sufficiently high, these data are not strictly homogeneous with those at lower levels. A regression was carried out using only the 68 observations made below 500 ft, and the results showed definite increase of the albedo with height. Linear and quadratic equations were fitted. The quadratic curve had a much narrower confidence band, and thus may be considered best to represent the data. The equation is

$$a = 0.1149 + 0.0146\,(z - \overline{z}) - 0.0022\,(z^2 - \overline{z^2}) \quad \ldots\ldots\ldots\ldots\ldots (1)$$

where a is the measured albedo, z is the height in hundreds of feet, $\overline{z} = 2.37$ and $\overline{z^2} = 7.00$. Note that the mean albedo for the low-level measurements is higher than that for all the data. This may be explained by the higher visibility below high stratus than below low stratus, corresponding to less haze when the stratus is high.

Using (1) to compute the albedo a_s of the sea surface ($z = 0$), we get 0.0957. This value is close to the value obtained by Burt with pyrheliometers near the sea surface. If this is the correct value, at least in coastal waters, the difference between it and the theoretical value of 0.066 must be due to scattering by particulate matter and bubbles below the surface.

POWELL and CLARKE [1936] give the results of three measurements of the fraction of incident radiation scattered back into the air by bubbles and particles in the water, namely, 0.03, 0.034, and 0.02. The average of these values, 0.028, is very close to the difference between the theoretical albedo and that determined by measurements over the sea. While their measurements of this fraction were not made under overcast skies, the values suggest that scattering below the sea surface is sufficient to account for the difference.

The question arises whether the increase in albedo with height represented by (1) is consistent with the amount of haze to be expected in the layer immediately above the sea. Neglecting absorption, the albedo at a level z in a cloud or haze layer is given [NEIBURGER, 1949] by

$$a = [a_s + F(z)\,(1 - a_s)]/[1 + F(z)\,(1 - a_s)] \quad \ldots\ldots\ldots\ldots\ldots (2)$$

where $F(z) = \int \alpha\beta\, dz$, α is the cross-sectional area presented by the haze particles per unit volume, and β is the fraction of incident radiation scattered backward by the particles. For completely diffuse radiation $\beta = 0.2$. Solving (2) for $F(z)$ and taking the difference between two levels z_1 and z_2 we obtain

$$\Delta F \equiv F(z_2) - F(z_1) = (a_2 - a_1)/(1 - a_2)(1 - a_1) \qquad (3)$$

But

$$\Delta F = \int_{z_1}^{z_2} \alpha \beta \, dz = \bar{\alpha} \beta (z_2 - z_1)$$

$$\bar{\alpha} = \Delta F / \beta (z_2 - z_1) \qquad (4)$$

Table 1 gives the pertinent data obtained from (1), (3), and (4).

Table 1--Scattering cross-section in haze below stratus cloud

z (ft)	a	ΔF	$\bar{\alpha}$ (cm^{-1})	k
0	0.0957			
100	0.1081	0.0154	2.5×10^{-5}	5.3×10^{-11}
200	0.1161	0.0101	1.7×10^{-5}	3.6×10^{-11}
300	0.1197	0.0046	0.76×10^{-5}	1.6×10^{-11}

JUNGE [1953] has shown that the particle-size frequency in the atmosphere has such a variation that, approximately

$$dN/d\log r = kr^{-3} \qquad r \geq r_o$$

$$dN/d\log r = kr_o^{-3} \qquad r_o/10 \leq r \leq r_o$$

where r_o is approximately 10^{-5} cm. If we assume this frequency distribution and that particles with radius less than 10^{-6} can be neglected, we obtain for α, by integration

$$\alpha = 1.495\,\pi k / r_o$$

If $r_o = 10^{-5}$, we get the values of k given in the table. For comparison, the value of k corresponding to Junge's data for Frankfurt is 0.7×10^{-11}. Table 2 gives the number in each size range if this form of frequency distribution was representative of the conditions when the observations were made.

Table 2--Computed particle-size distribution in haze below stratus overcast

Radius	Number per cubic centimeter		
	0-100 ft	100-200 ft	200-300 ft
micron			
0.01 - 0.1	1.2×10^5	8.3×10^4	3.7×10^4
0.1 - 1.0	1.8×10^4	1.2×10^4	5.3×10^3
>1.0	18	12	5.3

J. Y. Gilbert has made some counts of particle size in marine haze on the Los Angeles campus of the University of California. Table 3, quoted from unpublished data with his kind permission, gives data on two occasions of moderately low visibility. The samples were taken five miles from the ocean, at an elevation of 450 ft. The visibility was determined using markers generally at lower elevations and closer to the sea.

These actual counts of about 1000 particles between 0.1 and 1.0 micron in radius, and zero to five greater than 1.0 micron at 450 ft above sea level five miles from the sea suggest that the numbers given in Table 2, while large, are not unreasonable for salt haze off the coast. Woodcock's measurements of large salt particles over the ocean also give one per cubic centimeter as the order of magnitude of particles greater than one micron in radius.

Table 3--Particle-size distribution in marine haze at Los Angeles, determined by John Y. Gilbert

Radius	Number per cubic centimeter	
	August 24, 1953 Afternoon Visibility, 1.5-2 mi	August 25, 1953 Morning Visibility, 1.75-3.5 mi
microns		
0.1 - 0.25	617	951
0.25 - 0.5	164	246
0.5 - 0.75	84	47
0.75 - 1.0	14	10
1.0 - 1.25	4	...

It is to be expected that an average albedo of 0.095 for the sea surface under overcast is applicable to all coastal waters, where plankton and other particulate matter is plentiful in the surface waters. Whether the albedo is this high over the deep ocean can be decided only by measurement. For computations of the radiant energy absorbed by the ocean, however, it is clear that values of albedo larger than those computed from Fresnel's law must be used; and this applies to the direct radiation from the Sun as well as the diffuse radiation from the sky or through overcast clouds.

In the above the word albedo has been used in a generalized fashion, to express the fraction of downward radiation returned upward at a level by the matter at or below it. With this usage it is more proper to speak of the albedo at the sea surface rather than the albedo of it.

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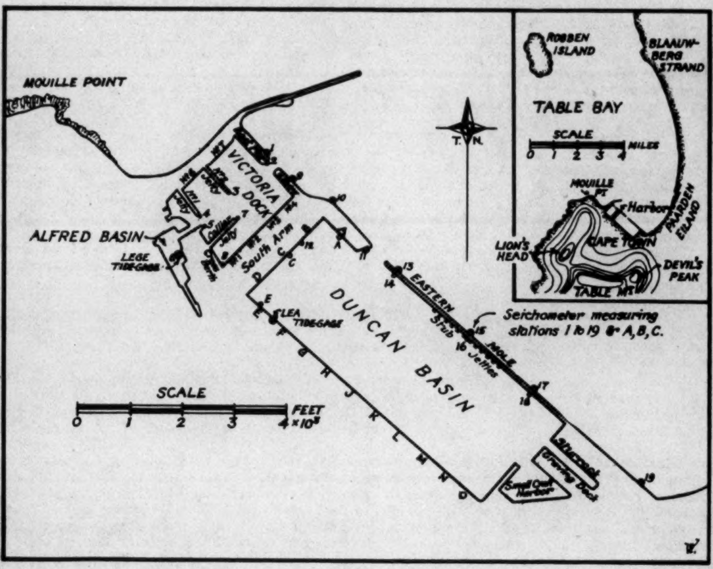
GENERATION OF LONG-PERIOD SEICHES IN TABLE BAY, CAPE TOWN, BY BAROMETRIC OSCILLATIONS

Basil W. Wilson

(Contribution from the Department of Oceanography of the Agricultural and Mechanical College of Texas, Oceanography and Meteorology Series No. 34)

Abstract--Table Bay Harbor, Cape Town, South Africa, is shown to be subject to two wave phenomena resulting from seiches in Table Bay and from smaller oscillations peculiar to the harbor itself. The lower-frequency seiches of the Bay usually attain appreciable amplitudes unaccompanied by swells such as induce seiches within the harbor basins. These longer seiches are not of seismic origin, but a positive correlation is established between their occurrence at Table Bay and Port Elizabeth and simultaneous barometric oscillations in the air mass overlying both centers. There is dangerously powerful fluxing of water through the entrances to harbors from this cause; the frequency of these effects at Cape Town varies from one or two to about 15 occasions per year. Specific examples emphasize the importance of the directional approach of the barometric oscillations. Southeast winds from the land, although inducing barometric oscillations as a result of standing wave formation in the lee of Table Mountain, fail to generate seiches. The suggestion is advanced that the seiches derive from the aerial commotion arising out of the coalescence of frontal depressions near the extremities of such fronts.


MOUILLE POINT
VICTORIA DOCK
ALFRED BASIN
LEGE TIDEGAGE
South Arm
DUNCAN BASIN
EASTERN MOLE
Stub Jetties
LEA TIDEGAGE
T. N.
Small Craft Harbor
Graving Dock
Seichometer measuring stations 1 to 19 & A, B, C.
SCALE
0 1 2 3 4 FEET ×10³
ROBBEN ISLAND
BLAAUWBERG STRAND
TABLE BAY
SCALE
0 1 2 3 4 MILES
MOUILLE PT
Harbor
PAARDEN EILAND
LION'S HEAD
CAPE TOWN
DEVIL'S PEAK
TABLE MT
1
9
10
11
12
13
14
15
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18
19
A
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Fig. 1--Table Bay and Harbor, Cape Town

Introduction--During researches into a phenomenon of surging in Table Bay Harbor, Cape Town, Union of South Africa (Fig. 1) over the period 1943-1946, it was noticed that marigrams of water movements in the harbor area showed in general two fundamentally different types of parasitic oscillations on the main semi-diurnal tide curves [WILSON, 1953a, 1953c, 1954]. Local storms with northwest winds from the sea and distant storms which failed to blow in to the port, but generated swells reaching the coast, all gave rise to oscillations in the harbor with periodicities predominantly in the range from 15 sec to about 17 min with greatest emphasis on the higher frequencies. These effects usually gave a dense embroidery to the marigram trace at paper speeds of one inch per hour and were normally referred to as range-action [WILSON, 1953b]. Quite a different (open) sort of trace was recorded on occasion by the superposition on the tide curve of large amplitude oscillations of long-period ranging predominantly between 15 and 70 min. This phenomenon, which occurred usually in fine weather, in the absence of heavy swell, and with negligible surface winds, was first noticed in 1943 and was at once thought to be associated with seismic sea disturbances.

Marigrams from Port Elizabeth (450 mi from Cape Town) showed an unmistakable correlation with those of Cape Town on several occasions in 1943 and 1944. Figure 2 is an example of this and reveals that simultaneous long-period seiches were in existence at both ports. As, however, no records of any associated antecedent seismic activity had been registered on seismographs in the vicinity, and there were also inconsistencies in the travel times of long waves and the relative times of occurrence of the disturbances at the two ports, the idea of a common seismic origin for the seiches at Cape Town and Port Elizabeth was abandoned. The phenomena were then re-examined in the light of meteorological conditions.

Barometric oscillations--Careful inspection of the barograms for Port Elizabeth and Cape Town soon revealed an embroidery indicative of atmospheric oscillations on each occasion that long-period seiches had been in evidence at the two places. In Figure 2 the barogram trace for Port Elizabeth, at the top of the diagram, is typical of these fluctuations. The corresponding barogram trace for Cape Town (Fig. 2) has irregularities which were probably comparable but are very much more subdued owing to the lower sensitivity of the Cape Town recording instrument.

Once this correlation had been recognized in 1944 it was possible to verify it infallibly in subsequent occurrences of the seiche phenomenon at Cape Town. Figure 3 is further evidence of this and portrays quite convincingly the genesis of typical long-period seiches in Table Bay as a result of oscillations in the atmosphere.

The sharp pressure-rise at 18h 30m (Fig. 3) seems to have acted like a plunger on the water surface of Table Bay and set in motion seiches of apparent periodicities 61, 45, 34, 25, and 20 min. The 'plunger' descended again at 20h 15m just as the seiche was welling up at the harbor end of the bay, as recorded on the harbor tide gages, and the seiche appears to have been damped promptly, although approximate 20-min air oscillations between 20h 15m and 21h 15m stimulated a corresponding 20-min seiche in the bay. At 22h 00m a sudden lifting of the pressure, followed half an hour later by the drop of the 'plunger' again set in motion once more the 34-min seiche and the ensuing upward and downward strokes of the 'plunger' were timed so well as to induce large oscillations in the bay. After about 02h 30m of April 9, the barometric disturbance died away and the seiches damped out.

Peculiarities of seiche phenomenon--The extremes to which water levels in the harbor could be affected by the seiches in Table Bay are well exemplified in Figures 4 and 5, from which it may be noted, in passing, that the phenomenon is as liable to occur at spring tides as at neaps.

The invariable accompaniment of prominent seiches at Cape Town is a strong reversible flux of water through the harbor entrances, more particularly in that of the large Duncan Basin (Fig. 1). On September 10, 1944 (Fig. 4), the currents in this entrance tore loose one end of the moorings of an anti-submarine boom defence, which at once became a dangerous lash, difficult to secure.

Instances are on record of ships having been carried out of control by the spate of the currents while navigating the basin entrances. Incidents on October 8, 1942, in a crowded harbor were subsequently shown to have been attributable to seiches. On this occasion (Fig. 6), a tug collided with a small naval vessel off the end of No. 1 Jetty in the Victoria Basin (Fig. 1), and the City of Canton (6692 gross tons) entering the Duncan Basin under steam with guidance from a tug was caught in an outgoing surge at the entrance and carried bodily sternwards outside the harbor. A short while later the Bankok II, a ship of about the same size, while leaving the Duncan Basin, grazed the north side of the bullnose at the entrance as a result of a strong set in the outgoing current.

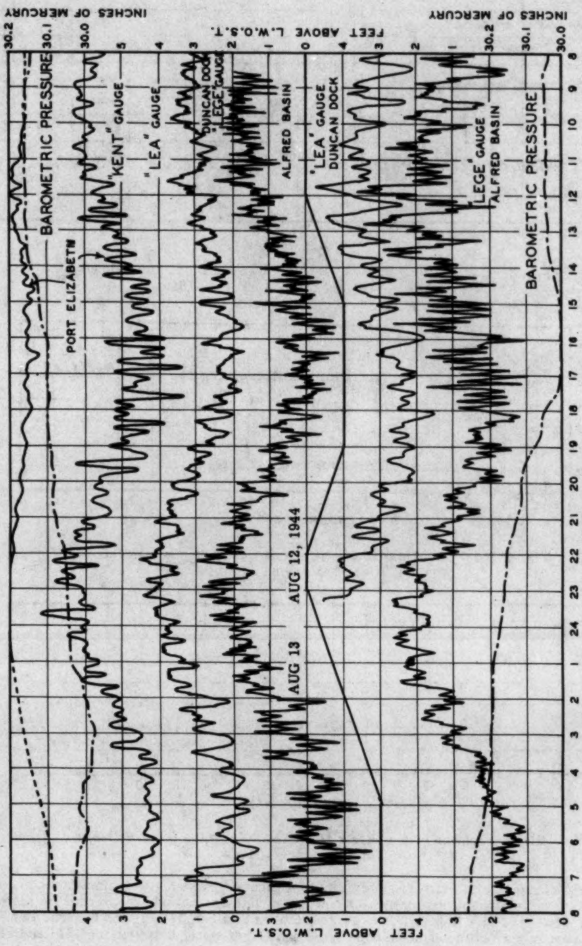

Fig. 2--Correlation between barometric oscillations and seiches in Table Bay, Cape Town, and Algoa Bay, Port Elizabeth, August 12-14, 1944

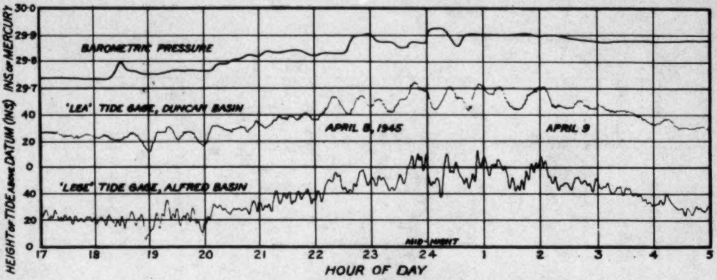

Fig. 3--Correlation between barometric oscillations and seiches in Table Bay, Cape Town, April 8-9, 1945

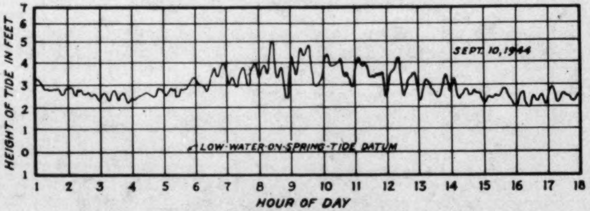

Fig. 4--Section of marigram from Lea tide gage, Duncan Basin, Cape Town, September 10, 1944

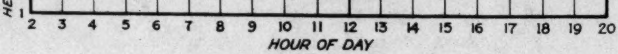

Fig. 5--Section of marigram from Lea tide gage, Duncan Basin, Cape Town, October 1, 1944

How these currents arise may be inferred from Figure 7, which gives simultaneous recordings of water level at a number of observing stations both inside and outside the harbor on the occasion of October 1, 1944 (see also Fig. 5). It is evident that at Stations 3, 4, 5, and 6 in the Duncan Basin there was virtually a simultaneous and equal rise and fall of water between 10h 45m and 11h 15m. This could only mean that the whole dock area increased its depth by some 30 inches in the interval

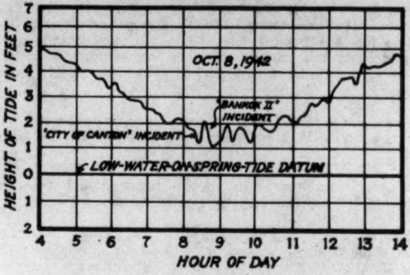

Fig. 6--Section of marigram from Lea tide gage, Duncan Basin, Cape Town, October 8, 1942

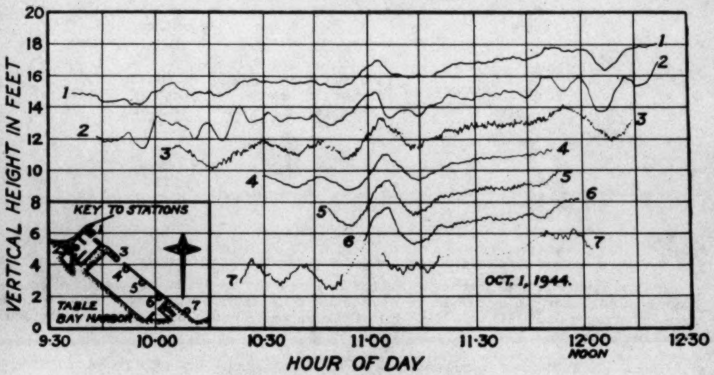

Fig. 7--Synchronized seichograms from seven observing stations, Table Bay Harbor, October 1, 1944

between 10h 55m and 11h 05m, necessitating an addition of water of 30 × 10^6 cu ft in ten minutes. This volume had to gain admittance through an entrance only 400 ft wide by 43 ft deep, and its average velocity of inrush would therefore have been about 3 ft/sec. Maximum velocity, estimated from the gradient of the records in Figure 7 must have been of the order of 5.5 ft/sec (3.3 knots) at this time.

On the basis then of a uniform rise or fall of water through a range H in a time T/2 (the half-period of the seiche), over the entire area of a dock, the average velocity of flow through its entrance will be

$$V = \alpha(2H/T) \quad \dots\dots\dots\dots\dots\dots\dots\dots (1)$$

if α is the ratio of the surface-area of the basin to the sectional area of its opening. An equal rise or fall of water in the Alfred, Victoria, and Duncan Basins, whose ratios α are respectively 1.9, 3.1, and 7.5 (× 10^2), would cause respective velocities of flow in the three basins in the proportions 1 : 1.5 : 4. Conditions producing a four-knot current through the Duncan Basin entrance would thus induce only 1.0- and 1.5-knot currents at the mouths of the Alfred and Victoria Basins respectively.

Conversely, seiches of the same magnitude H, but different periodicities T, inducing equal velocities V in the three basin entrances, must, from (1), have periodicities in the proportion of the ratios α. Hence, if (as has been found) a seiche of 18-min period can induce a four-knot current through the Duncan Basin entrance, like currents can only be produced in the Alfred and Victoria Basin entrances, if the exciting seiches have periodicities of 4.5 and 6.75 min respectively and are of equal amplitude.

While it may be recognized from this that, given the right conditions, surge in small harbor basins can be just as powerful as in large basins, it will usually reverse more rapidly and be less of a sustained millrace.

The danger to shipping from long-period seiches resides then in the navigation hazards at basin entrances. Ships at the quays are relatively unaffected.

Frequency of occurrence and magnitude of long-period seiche--Occurrences of prominent long-period seiches at Cape Town were found to be relatively infrequent. Table 1, based on marigrams for the harbor area, covers the period 1940 to 1946 and shows about six annual occurrences on the average. A noticeable feature of that period was that years which yielded few incursions of long-period seiches (1940-1942) produced a considerable crop of serious range-action troubles from the higher frequency seiches, and, vice versa, years that were lean in bringing the latter phenomena (1943-1946) gave rise to more frequent and prominent long-period seiches.

Table 1--Frequency of occurrence of long-period seiches, Table Bay Harbor, 1940-1946

Year	Number of occurrences	Annual occurrences with simultaneous short-period seiches	Maximum height of seiches
			inch
1940	4	. . .	30
1941	3	. . .	16
1942	1	. . .	11
1943	7	. . .	18
1944	6	. . .	32
1945	15	2	24
1946	10	2	28

Note in Table 1 that there is an obvious tendency for large-amplitude long-period seiches and large-amplitude short-period seiches to occur on distinctly separate occasions. On the two occasions listed in 1945 and 1946 when short-period seiches were co-existent, amplitudes of the latter were quite minor.

These apparently opposite characteristics suggest that the meteorological conditions giving birth to the two phenomena are fundamentally different.

Meteorological correlations--By way of attempting to correlate occurrences of long-period seiches with local weather conditions, in the light of meteorological data available, three specific examples are considered in Figures 8, 9, and 10 which are composite charts on which continuous barometer and anemometer recordings for the dock area have been drawn in to the same time-scale as the Lea-gage marigram for the Duncan Basin.

Example 1: September 24-27, 1945--Noticeable features of the occasion (see Fig. 8) were the clear, calm weather, negligible surface winds (average velocity under ten miles per hour) with a drift from the open sea to the northwest, and pronounced barometric oscillations on a rising pressure gradient. High-frequency sea oscillations were conspicuously absent in the early stages of the development.

Association between the barometric oscillations and sea seiches on September 24 is again apparent, but it may be remarked that further barometric fluctuations of somewhat smaller amplitude on September 27 failed to induce any sea response out of the ordinary. It should be noted, however, that the over-riding air mass had by then veered to the southeast, with a drift from the opposite landward quarter.

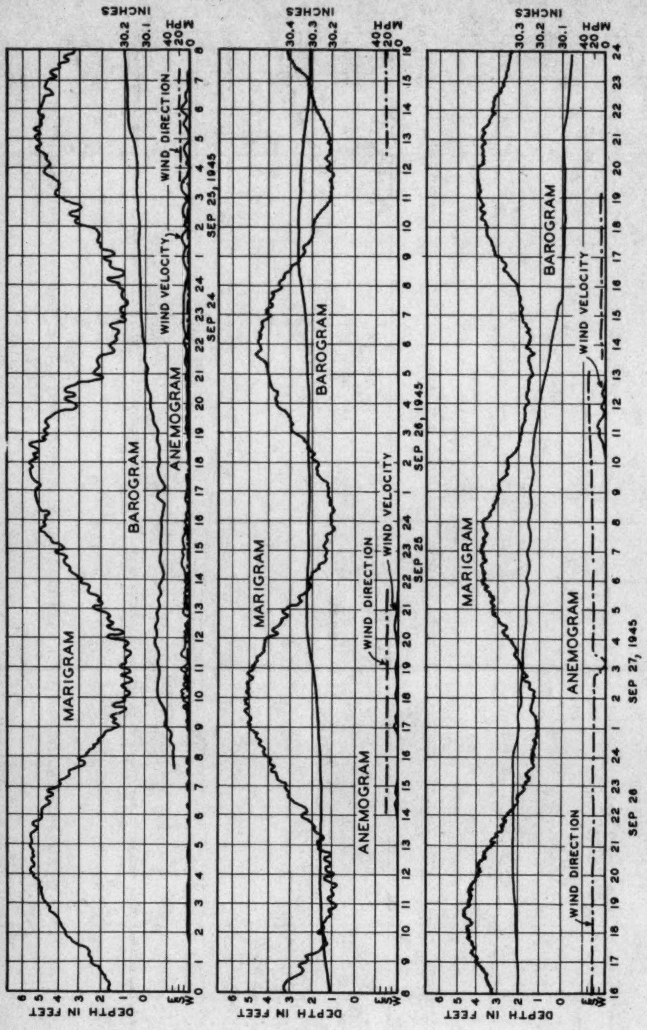

Fig. 8--Correlation between seiches in Table Bay (Lea recorder) and local weather, September 24-27, 1945

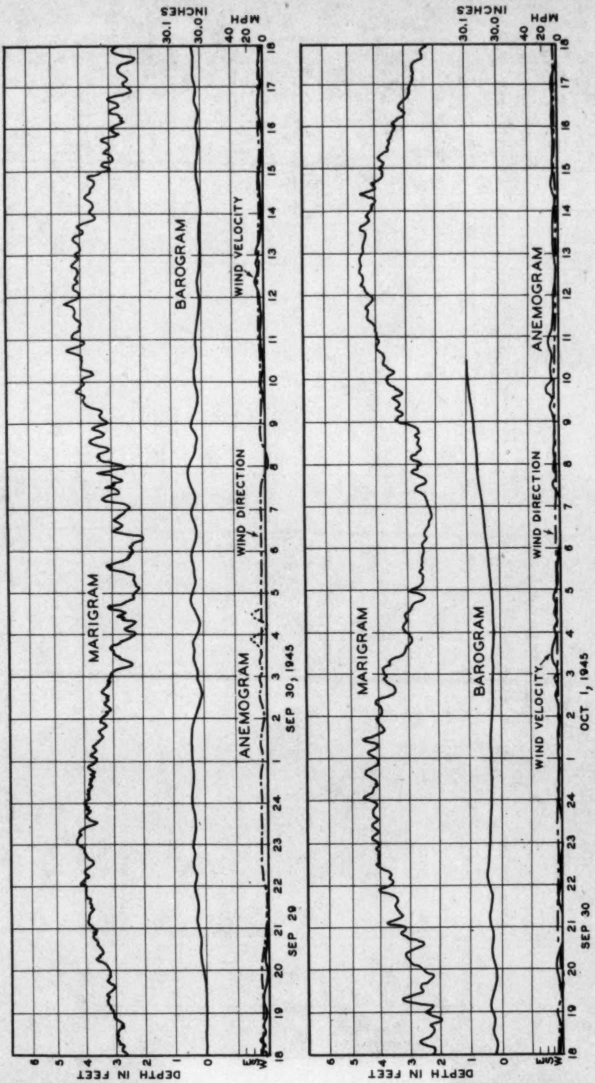

Fig. 9--Correlation between seiches in Table Bay (Lea recorder) and local weather, September 29-October 1, 1945

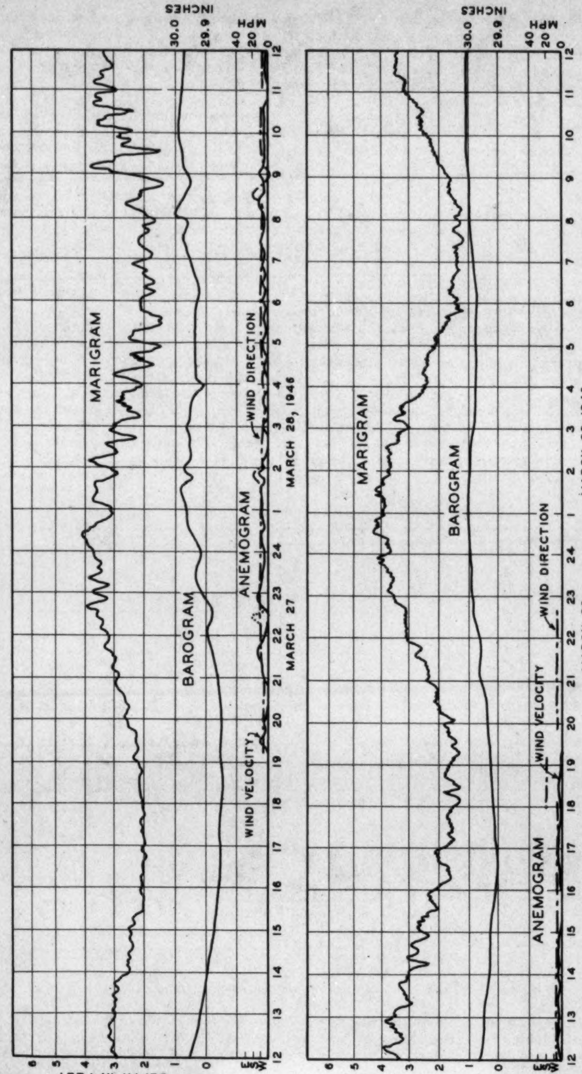

Fig. 10--Correlation between seiches in Table Bay (Lea recorder) and local weather, March 27-29, 1946

Example 2: September 29-October 1, 1945--Figure 9 shows the situation a few days after that of Example 1. Pronounced barometric oscillations of relatively pure form in an overlying air mass that was drifting over Cape Town from the northwest at negligible surface velocity are responsible for the large seiches imposed on the waters of Table Bay. Undulations in wind velocity and direction, in apparent conformity with the pressure variations, are noticeable.

Example 3: March 27-29, 1946--The extraordinary sea oscillations of Figure 10 were engendered by powerful barometric oscillations on the rising pressure gradient of an anticyclone moving over Cape Town from the northwest. Again the weather was calm and clear, and the surface wind almost negligible.

Approximate harmonic analysis of the pressure record suggests the existence of atmospheric waves with periods of the order of 130, 82, 66, 36, and 15 min. Wind velocity and direction are likewise found to fluctuate in an unmistakably periodic manner, and the most prominent variation, significantly, is in accordance with the 36-min component of the pressure oscillations.

Directional approach of air oscillations--The circumstance in Example 1 that barometric oscillations from the southeast failed to generate long-period seiches of any significance is attributed to a fundamental difference between such atmospheric oscillations invading the scene of Table Bay from the northwest and the southeast. Observation showed that oscillations from the southeast were invariably tail-end waves of powerful surface currents of air, whereas those from the northwest were apparently always associated with insignificant surface winds. In further illustration of this difference it will be seen from Figure 11a that barometric oscillations were in evidence on at least five occasions during September, 1945. On two of these occasions (September 24 and 30) when the wind-drift was from the northwest, seiches occurred in Table Bay as already remarked in Figures 8 and 9. On the occasions of September 13 and 17 strong surface winds from the southeast were blowing off the land, giving rise to prominent barometric and wind oscillations (Fig. 11bc), but failing to excite any seiches in the bay. The periodicities evident in the anemograms for these two occasions are about the same (34 to 38 min) and correspond with the barometric oscillations.

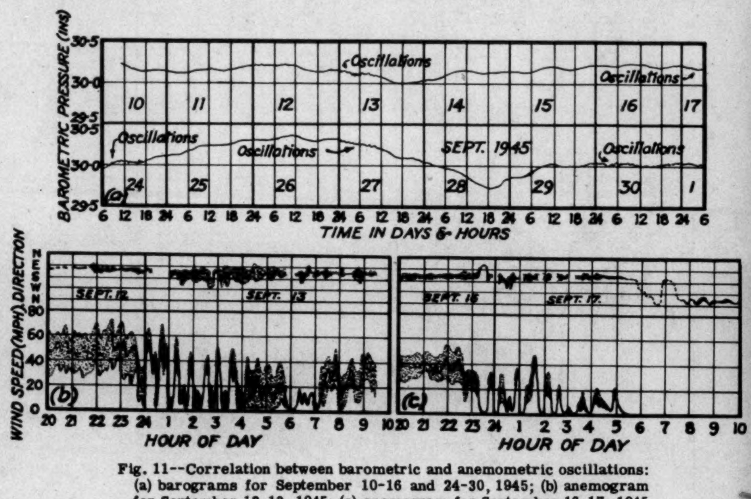

Fig. 11--Correlation between barometric and anemometric oscillations: (a) barograms for September 10-16 and 24-30, 1945; (b) anemogram for September 12-13, 1945; (c) anemogram for September 16-17, 1945

The explanation for all this must presumably reside in the fact that atmospheric waves advancing from the northwest (that is, the open sea) have the best directional approach for exciting seiches in the bay since their pressure disturbances ensure a train of forced long sea-waves. On the other hand, atmospheric waves advancing from the southeast supply only superficial energy to the sea from the landward side and seem incapable of sustaining any large seiches in the presence of the frictional damping of the strong surface winds.

The air waves from the northwest, since they produce only small surface winds, yet, withal, create pressure variations of the order of up to two mb, must presumably be fairly high level oscillations of the atmosphere. The air waves from the southeast on the other hand are obviously shallow depth oscillations and may reasonably be attributed to the Table Mountain barrier.

Any air stream passing over the dock area at Cape Town from the southwest, south, or southeast must previously have ascended the inclined plateau forming the mountainous backbone of the Cape Peninsula (Fig. 1, inset). At an altitude of some 3800 ft it would leave the sheer crescent-shaped escarpment of Table Mountain and develop standing waves on the leeward side in much the same way that standing waves are observed to occur on the downstream side of obstructions in moving currents of water. Standing wave formations of this kind in the atmosphere are now familiar phenomena [QUENEY, 1947].

The standing waves from a southeasterly surface wind would not ordinarily produce any variation of barometric pressure or wind intensity at an observing station on the leeward side of the mountain until such time as the overall speed of translation of the air mass suffered a change. In the event of the wind tailing out, the standing waves could be expected to become waves of propagation and would then register barometrically and anemometrically at the observing station.

That such standing waves do occur over the northern side of Table Mountain has been demonstrated by the feats of pilots of the Cape Town Gliding Club in soaring on the uplift pressure of the waves to altitudes of 13,000 ft.

Seiches in relation to the coalescence of frontal depressions--The only occasion on which seiches in Table Bay were ever found to be in existence during a fluctuating southeast wind is portrayed in Figure 12. On September 1, 1946, these seiches were quite minor until the wind virtually died away and strong barometric undulations set in, presumably as a result of a warm sector air mass moving in aloft from the northwest and destroying locally the momentum of the southeast surface stream. The possibility of this being the case suggests an explanation for the general phenomenon of coastal seiches deriving from pressure fluctuations in the atmosphere. It would seem that it might be related to frontal occlusion or the overrunning of separate air currents in the breaking wave action [FREEMAN, 1952] of mature or exhausting cyclones.

The case of October 1, 1944, already referred to (Fig. 5 and 7), may be examined in this light with the aid of the synoptic charts of Figure 13 which cover the period. The suggestion of Figure 13 is that occlusion of cold fronts C and D occurred over the South African coast at precisely the time that barometric oscillations developed and caused seiches in Table Bay.

A second case for which information is available is that of April 8-9, 1945, already featured in Figure 3. The synoptic charts of Figure 14 cover this period and show an occluding depression, A, closing in on a stationary low-pressure center, B. Again support is obtained for the belief that both air and sea oscillations are the direct repercussion of one frontal wave overtaking another.

Quite independent support for this concept is furnished by ABDULLAH's [1949] explanation of cyclogenesis arising out of the purely mechanical process of a frontal wave pushing behind a quasi-stationary front [see also TEPPER, 1952]. In this process the faster-moving front at the rear heaps before it, increasing quantities of cool air from behind the stationary front, thereby imparting energy to the latter and causing it to move forward eventually at a faster relative speed than its disturbing agency in the rear. The forward front becomes increasingly steep from this action until it forms an overhanging nose of cool air which finally breaks after the fashion of a tidal bore.

The general observation made earlier that the frequency of long-period seiches seems highest when that of ordinary range-action is lowest suggests that there is a greater tendency toward the first disturbance when the tracks of traveling cyclones are farther south and sources of swells and ordinary range-effects are therefore more distant. The notable lessening of the intensity of range-action at Cape Town from 1943 onwards and its resurgence again more recently (1951-1952) seems to suggest that there may be a slow periodic shift of the atmospheric high pressure belts in both hemispheres to north and south of their mean positions, dictated possibly by the sunspot cycle of solar radiation. Such a mutation of the high pressure belt southward in the southern hemisphere would deflect the centers of traveling depressions farther from the South African coast and bring

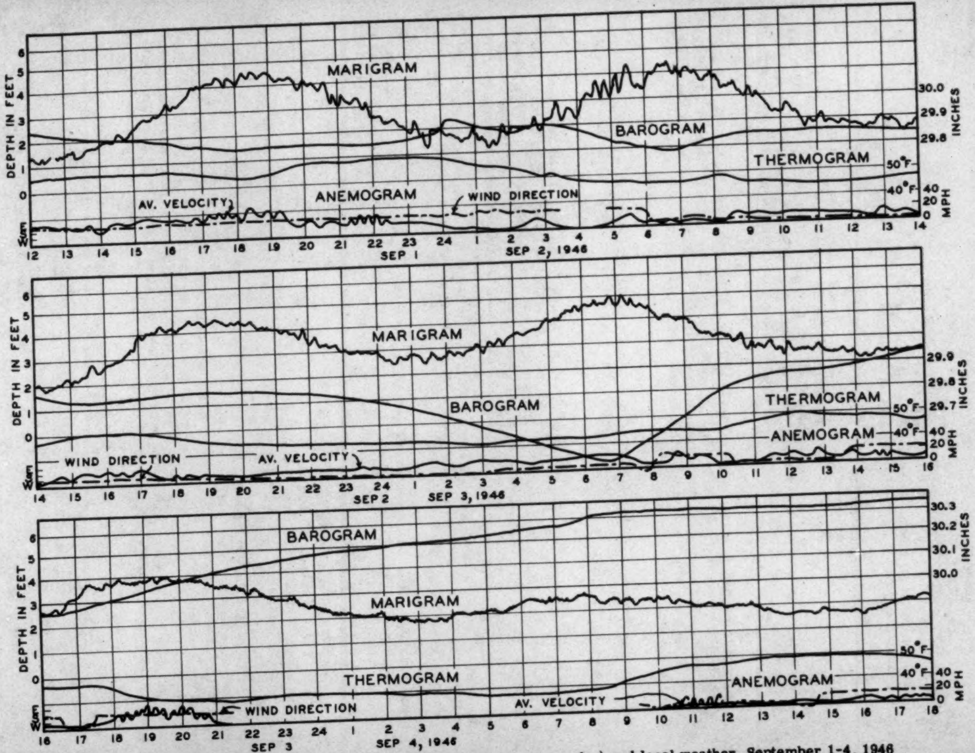

Fig. 12--Correlation between seiches in Table Bay (Lea recorder) and local weather, September 1-4, 1946

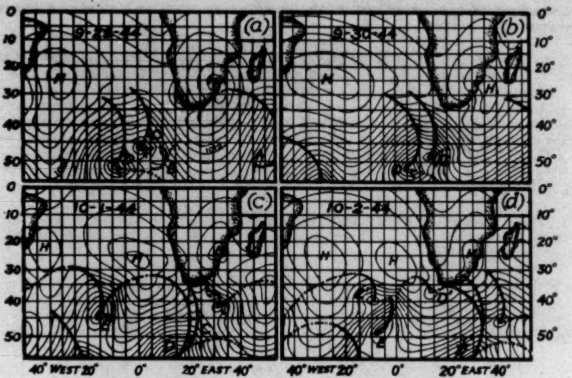
(a)
9-29-44
(b)
9-30-44
(c)
10-1-44
(d)
10-2-44
0
10
20
30
40
50
0°
10°
20°
30°
40°
50°
40° WEST 20°
0°
20° EAST 40°
H
L

Fig. 13--Daily synoptic charts (00h 30m GMT) for South Atlantic Ocean, September 29-October 2, 1944

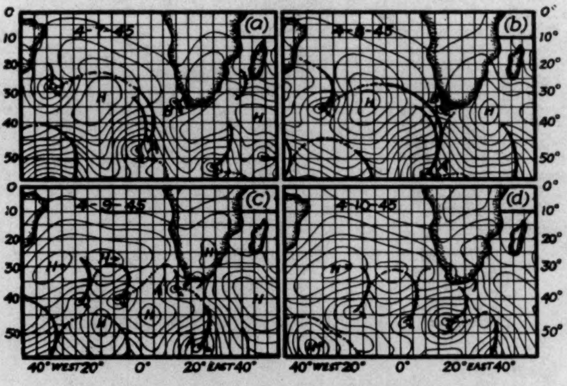
(a)
4-7-45
(b)
4-8-45
(c)
4-9-45
(d)
4-10-45
0
10
20
30
40
50
0°
10°
20°
30°
40°
50°
40° WEST 20°
0°
20° EAST 40°
H
L

Fig. 14--Daily synoptic charts (00h 30m GMT) for South Atlantic Ocean, April 7-10, 1945

the extremities of the cold fronts to bear more upon Cape Town, and it is suggested that in the movements of the anticyclones in these regions of the cold fronts may be found the clue to the barometric oscillations and accompanying coastal seiches described in this paper.

Summary and conclusions--Surging in Table Bay Harbor, Cape Town, has been identified as occurring in two forms which for the most part are distinct in character and occurrence. The coastal seiche phenomenon, with which this paper deals more specifically, produces very powerful and prolonged fluxes of water through the entrance to the large Duncan Basin -- fluxes which are dangerous to ship navigation but create no trouble at the quays. In contradistinction, the second phenomenon of range-action, which is known to be associated with swells originating from distant storm centers, produces short, powerful pulses through the smaller Victoria and Alfred Basin entrances and is characterized by the troublesome motion it communicates to ships at their berths in the harbor.

The coastal seiches are shown to be excited by prominent pressure fluctuations in the overlying atmosphere when the wind drift is from the open sea. These oscillations in the atmosphere show a consistency on different occasions, which, upon analysis, suggest the existence of air-wave trains with periods in the neighborhood of 130, 82, 66, 36, and 15 min. Similar coincidental periodicities have been detected at Port Elizabeth, 450 mi from Cape Town, and obviously derive from a common meteorological source. The excitation of strong coastal seiches at both Port Elizabeth and Cape Town would seem to derive from the fact that some of the natural frequencies of oscillation of Table Bay and Algoa Bay are in close agreement with the periods of the air waves, the seiches of Table Bay commonly showing periodicities in the ranges 70-50, 33-26, and 23-15 min.

A necessary condition for the generation of the seiches would seem to be that the direction of approach of the air waves be from the open sea. Air waves off the land ordinarily fail to stimulate coastal seiches.

Those long-period atmospheric waves that originate with air streams from the northwest off the sea would appear to be related to the interference of one depression with another, and it is suggested that they mark the effects of a frontal depression wave being suddenly dissipated by the retarding effects of a slower antecedent front. Other long-period air waves, found in the tail movements of strong surface currents of air moving over the Cape Penisula from the southeast, are clearly in a different category, and appear to originate as standing waves on the lee side of the mountain.

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AN INTERPRETATION OF THE OBSERVABLE PROPERTIES OF 'SEA' WAVES IN TERMS OF THE ENERGY SPECTRUM OF THE GAUSSIAN RECORD

Willard J. Pierson, Jr.

Abstract--The results of a basic paper in communication theory by Rice are applied to ocean waves. On the basis of new results obtained by Neumann on the nature of wave spectra, many complicated properties of the waves are explained theoretically. It is shown that the average of the time intervals between successive crests does not yield a 'period' which is representative of the period where most of the spectral energy is concentrated. It is shown that the formula $L = gT^2/2\pi$ does not apply to sea conditions. An explanation of the 'period' increase of ocean swell is given which does not depend upon selective attenuation of the low period waves in the spectrum.

Wave properties to be shown in this paper--It will be shown

I.

$$\frac{\overline{\overline{T}}_D}{\overline{\overline{T}}_F} \leq \sqrt{2} \quad \ldots\ldots (1)$$

$\overline{\overline{T}}_F$ is the average time interval between successive crests in the generating area. $\overline{\overline{T}}_D$ is the average of the time intervals between the successive crests of the highest swell to pass a point outside of the generating area.

II. In a sea

$$\overline{\overline{L}}_o = \frac{2}{3}\,\frac{g\overline{\overline{T}}^2}{2\pi} \quad \ldots\ldots (2)$$

$\overline{\overline{L}}_o$ is the average distance between the successive crests at a fixed time; and $\overline{\overline{T}}$ is the average time interval between the crests.

III. There are 73 pct more wave maxima in a wave record than there are waves.

IV. The fully developed sea is in a completely unstable state and additional energy from the wind will probably result only in the formation of more breakers and more white caps without an additional increase in the height of the waves.

V. If a storm is moving in the direction of the wind in the storm at the speed of the wind in the storm, then the waves cannot travel out of the area of the storm. This would mean, for example, that an approaching cold front would not herald its arrival by waves propagating out in advance of the front. The waves will jump to full amplitude in a matter of a few hours during the frontal passage.

Two definitions of "period"--Confusion constantly arises due to the loose interchange of the two possible meanings of "period." The popular meaning is confused with the meaning of the word in the exact mathematical sense.

The mathematical definition of period as given by JAMES and JAMES [1949] (with notation changed slightly) is as follows: "Periodic function of a real variable--A function, $\eta(t)$, such that the range of the independent variable can be divided into equal sub-intervals such that the graph of the function is the same in each sub-interval. The length of the smallest [of] such equal sub-intervals is called the period of the function. If $\eta(t) = \eta(t + T)$ for all t, and T is the smallest number greater than zero for which such a relation holds, then T is the period of the function. Cos $2\pi t/T$ has the period, T, since $\cos 2\pi(t + T)/T = \cos 2\pi t/T$."

In popular terminology, the above definition is seldom applied to waves. For example, BARNHART [1951] defines 'period' as follows: "Period 3--The time of one complete cycle of a vibration, current, etc." and 'cycle' as: "Cycle 1--Period of time or complete process of growth or action that repeats itself in the same order." Thus, 'period' is defined in terms of 'cycle,' and 'cycle' in terms of 'period.' Neither definition implies that the representation of the function repeats itself exactly every T seconds.

For the actual sea surface, the time interval between two successive crests might be the 'period' of a 'cycle' in the loose popular sense. It certainly is not the period in the exact mathematical sense of the word. In this paper whenever the true period is meant, period will be underlined in what follows; whenever the popular definition is meant, 'period' will have quotation marks around it.

The popular definition of 'period' does not require that the wave record repeat itself exactly. A wave record can have different 'periods' in the same record. It is then necessary to define an average 'period' for theoretical purposes. The average 'period,' then, in terms of an extension of the popular definition, is the average of the time intervals between the successive crests of a wave system as observed at a fixed point of observation. When the wave length and period of a periodic function are discussed, the symbols will be L and T. If the average 'period,' in the popular sense, is referred to, the symbol will be $\tilde{T}$. Similarly, $\tilde{L}$ designates the average 'wave length.'

The classical formulas for wave motion were derived from a mathematically defined periodic simple harmonic function. Under these conditions, $L = gT^2/2\pi$ is a correct formula. Such a relation is not true for the average 'period' and the average 'wave length' of the actual sea surface. Formulas will be derived on the basis of the theoretical power spectrum derived by NEUMANN [1953] which will show what the correct relations are.

Sine waves and sea waves--First it is necessary to discuss the properties of the simple harmonic progressive wave as given by

$$\eta(t) = A\cos\frac{2\pi t}{T} \qquad (3)$$

Eq. (3) shows what would be observed as a function of time at a fixed point if a simple harmonic wave were passing that point. With proper added conditions, it is possible to conclude that the waves as a function of x look like

$$\eta(t) = A\cos\left(\frac{4\pi^2 x}{gT^2} - \frac{2\pi t}{T}\right) \qquad (4)$$

Under special restrictive conditions, the classical formulas hold. Ocean waves do not look like (3) or (4), and therefore the classical formulas cannot hold for ocean waves.

The formula which most nearly represents a wave record as observed as a function of time at a fixed point is given by (5). This formula in connection with ocean waves was presented by PIERSON [1952], and it is discussed also in a paper by PIERSON and MARKS [1952].

$$\eta(t) = \int_0^\infty \cos[\mu t + \psi(\mu)]\sqrt{[A(\mu)]^2 d\mu} \qquad (5)$$

$$\eta(t) = \lim_{\substack{\mu_{2r}\to\infty \\ \Delta\mu\to 0}} \mathrm{Re}\sum_{n=0}^{r} e^{i(\mu_{2n+1}t + \psi(\mu_{2n+1}))}\sqrt{[A(\mu_{2n+1})]^2(\mu_{2n+2}-\mu_{2n})} \qquad (6)$$

Eq. (5) can be represented as the limit of the partial sum given in (6). $\psi(\mu)$ is a function chosen in random phase. The limit is the classical random walk problem. The projection then gives the wave record.

In the limit, the projection of the sum of vectors into the real axis for any particular value of t is a sample from a normal population with a second moment given by E/2 as stated in (7). E is defined by (8). It can also be found by computing twice the average square of the departure of a wave record from zero.

$$P(-\infty < \eta(t) < K) = \frac{1}{\sqrt{\pi E}} \int_{-\infty}^{K} e^{-\xi^2/E}\, d\xi \tag{7}$$

$$E = \int_0^\infty [A(\mu)]^2\, d\mu \tag{8}$$

The function $[A(\mu)]^2$ can best be termed the energy spectrum. In previous works by the author, it has been called the power spectrum in analogy to a similar function in electronic theory. However, the spectrum in ocean wave theory is more nearly related to the potential energy averaged over time at a fixed point as (9) states.

$$\overline{PE}^{t} = \frac{\rho g E}{4} \tag{9}$$

With the sea surface represented at a fixed point as a function of time by an equation like (5), it can be seen that there is no reason why the simple formulas for 'wave length,' wave 'period,' and wave crest 'speed' that are true for simple harmonic progressive waves should hold for the actual sea surface. Why should they? After all, the waves of the actual sea do not remotely resemble a simple harmonic progressive wave. The simple fact of the matter is that they do not follow the laws for classical waves, and it is necessary to investigate the properties of waves on the actual sea surface in a more rigorous and careful manner in order to find out exactly what properties they have.

Analogous formulas, however, do hold. These formulas relate measurements such as the average time interval between successive crests and the average distance between the crests to the spectral properties of the disturbance as given by the function $[A(\mu)]^2$.

Results of Neumann--NEUMANN [1953] has presented a derivation for the energy spectrum of a fully developed sea surface on the basis of theoretical investigation and on the basis of visual observations made by him. This theoretical energy spectrum is given by (10) where the constant c is 4.80×10^4 cm^2 sec^{-5}. The spectrum has the dimensions of cm^2 sec. The symbol μ is an angular frequency, g is the acceleration of gravity, and the velocity v is the wind velocity in cm/sec. If the winds have blown long enough with a constant direction over the surface of the sea, then this function represents the energy spectrum of the fully developed state of the sea

$$[A(\mu)]^2 = \frac{c}{\mu^6} e^{-2g^2/\mu^2 v^2} \tag{10}$$

The maximum of the spectrum as discussed by NEUMANN [1953] is given by

$$\mu_{MAX} = \sqrt{\frac{2}{3}}\ \frac{g}{v} \tag{11}$$

Eq. (11) can also be put into the form

$$\frac{gT_{MAX}}{2\pi v} = \sqrt{\frac{3}{2}} = 1.22 \tag{12}$$

There is a temptation to relate the value, $gT_{max}/2\pi$, to a wave crest 'speed,' but in reality very little is known about the 'speed' of actual ocean wave crests. The formula means only that the spectral components at the maximum of the spectrum in the total sum of sinusoidal terms which make up the complex sea have a speed which is 1.22 times the wind velocity.

The spectrum has the property that it is essentially zero for frequencies which correspond to group velocities greater than that of the wind. It rises very rapidly for slightly higher frequencies to a maximum given by (11), and then it falls off like one over the frequency to the sixth power to zero at infinity. This spectrum is important because it will explain many of the seeming discrepancies which have been found in visual observations, and it will help explain the 'period' increase of ocean swell, the inconsistencies in past visual observations, and the actual mechanism by which ocean waves are generated.

The spectrum derived by Neumann has no energy in it for frequencies which correspond to periods associated with group velocities greater than or equal to the velocity of the generating wind. Therefore, if the forward edge of the generating area is traveling with the speed of the wind in the direction of the wind, as a cold front actually does, no waves can travel out of the area to reach a distant point before the area itself arrives. Statement V is therefore proved. This phenomenon has been observed many times by Atlantic Weather Patrol personnel.

The results of Rice--In a classical paper, RICE [1944] presented a complete mathematical description of the electronic voltages produced by random noise in communication theory. Nearly all the results of Rice can be carried over and expressed in terms of the properties of ocean waves.

Rice gave the probability distribution function for the envelope of the function defined by (5) under the condition that the spectrum be narrow. Reference to the work of LONGUET-HIGGINS [1952] and WATTERS [1953] is made in this connection. The concepts of the significant height and the average height are precisely defined by these results.

Average 'period'--A very interesting application of the results of RICE [1944] can be found by interpreting some of the formulas which he presents in terms of the average time interval between the crests of the waves that pass a fixed point. The crest is a rather difficult thing to define, especially in a record where there may be several maxima before the function goes back through the value of zero. Rice therefore studied the expected number of zeros in a Gaussian noise. As the record oscillates back and forth it goes through zero every once in a while; and if the number of zeros in a given length of record is computed, it is possible to state the average number of zeros per second in the record.

In order to apply the results of Rice most easily, it is necessary to express the equations given above in terms of frequencies instead of angular frequencies. To do this, let μ equal $2\pi f$ where f is the reciprocal of the period. Then the spectrum becomes (13), the representation of the sea surface given in (5) becomes (14), and the spectrum given in (10) becomes (15).

$$[A(\mu)]^2 d\mu = [A(f)]^2 2\pi df = [A(f)]^{*2} df \quad \ldots\ldots\ldots (13)$$

$$\eta(t) = \int_0^\infty \cos\left[2\pi f t + \psi(2\pi f)\right] \sqrt{[A(f)]^{*2} df} \quad \ldots\ldots\ldots (14)$$

$$[A(f)]^{*2} = \frac{2\pi C}{(2\pi)^6 f^6} e^{-2g^2/4\pi^2 \upsilon^{-2} f^2} \quad \ldots\ldots\ldots\ldots (15)$$

Since there must be a zero up-cross associated with every zero down-cross, one-half the expected number of zeros in a Gaussian noise gives a value for the expected number of zero up-crosses. A zero up-cross is defined to be a point on the record where the graph of the record crosses zero from negative to positive values.

The formula for the expected number of zero up-crosses is then given by (16). The high frequency components are more important because they are multiplied by f^2. The average time interval between the zero up-crosses is the reciprocal of this number as given by (17), and evaluation of the integrals then yields (18). Thus the ratio of the wave crest speed associated with the 'period' which measures the average time interval between the successive zero up-crosses of a wave record to the wind velocity is $\sqrt{3}/2$. This means that the average time interval between the zero up-crosses is a number which is considerably smaller than the value of the period associated with the maximum of the spectrum of the waves as given in (12).

The ratio of (12) to (18) can then be computed. The result is (19). The ratio of the period associated with the maximum of the spectrum to the 'period' associated with the average time interval between successive zero up-crosses is $\sqrt{2}$. The value given by (18) is most nearly equal to the value reported for a sea as evidenced by the results of CORNISH [1934] in his early investigations.

$$\bar{f}_{\substack{\text{ZERO}\\ \text{UP-CROSSES}}} = \left[\frac{\int_0^\infty f^2 [A(f)]^{*2} df}{\int_0^\infty [A(f)]^{*2} df}\right]^{\frac{1}{2}} \qquad \text{(16)}$$

$$\bar{\bar{T}} = \left[\frac{\int_0^\infty T^4 e^{-2g^2T^2/4\pi^2 v^2} dT}{\int_0^\infty T^2 e^{-2g^2T^2/4\pi^2 v^2} dT}\right]^{\frac{1}{2}} \qquad \text{(17)}$$

$$\frac{g\bar{\bar{T}}}{2\pi v} = \frac{\sqrt{3}}{2} = 0.866 \qquad \text{(18)}$$

$$\frac{T_{MAX}}{\bar{\bar{T}}} = \frac{\bar{\bar{T}}_D}{\bar{\bar{T}}_F} = \sqrt{2} \qquad \text{(19)}$$

Number of maxima--There are more wave maxima in a wave record than there are wave crests, or stated in another way, the number of maxima in a wave record exceeds the number of zero up-crossings. A maximum is a point on a record where the record has a horizontal tangent and where the curvature is positive. There can be several maxima between two zeros, and there can be maxima down in the troughs of the waves according to this definition. An irregular sea record has many such maxima, and they can be considered to be additional wave crests.

Rice has also presented a formula for the expected number of maxima in a Gaussian noise, and in terms of wave theory this yields (20). Upon the substitution of the spectrum given by Neumann, the result is (21). The average time interval between the successive maxima of a wave record, $\tilde{T}_m$, then gives a ratio of crest speed at that 'period' to wind velocity equal to 0.5. This value is less than the ratio obtained in either (12) or (19).

The ratio of (21) to (18) is (22). This means that there are 73 pct more wave maxima in a fully developed sea wave record than there are zero up-crosses. There are more wave crests on the surface of the ocean than there are waves.

$$\bar{f}_{MAX} = \left[\frac{\int_0^\infty f^4 [A(f)]^{*2} df}{\int_0^\infty f^2 [A(f)]^{*2} df}\right]^{\frac{1}{2}} \qquad \text{(20)}$$

$$\frac{g\tilde{T}_m}{2\pi v} = \frac{1}{2} \qquad \text{(21)}$$

$$\frac{\overline{\overline{T}}}{\overline{\overline{T}}_m} = \sqrt{3} = 1.732 \quad \ldots\ldots\ldots\ldots\ldots\ldots (22)$$

Relation to the visual properties of a wave record--These results begin to make it possible to describe what we actually see when we see the sea. Figure 1 shows a sample wave record as it might appear at a fixed point. This record shows 14 complete waves and ten other maxima, a total of 24 maxima on this record. Zero time is at t_0 at the far left of the record where the graph of the record goes through its first zero up-cross, t_1 is the time of occurrence of the first full wave crest, t_2 is the second zero up-cross, and so on. If the record shown in Figure 1 is, for example, 150 sec long, then t_{27} equals 145 sec with five seconds more needed to go from crest No. 14 to the last zero down-cross.

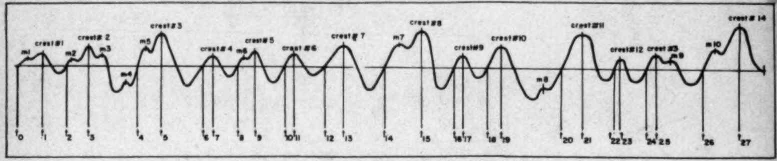

Fig. 1--Sample wave record

In the popular definition of the word, 'period' usually refers to the time interval between two successive dominant crests in a wave record. For example, in Figure 1 the 'period' of the first wave would be $t_3 - t_1$. Define $\overline{T}^*$ to be the average of these wave 'periods' as given by (23). If the summation given in (23) is expanded, the whole formula then collapses to give the second result. Dominant refers to the highest part of the record following a zero up-cross and preceding a zero down-cross.

$\overline{\overline{T}}$ is defined in (18) to be the average time interval between the successive zero up-crosses. $\overline{\overline{T}}$, then, in terms of an actual wave record, can be represented by (24). When the expression is expanded, the same thing occurs as in (23).

The relationship between $\overline{\overline{T}}$ and $\overline{T}^*$ is then not too difficult to compute. It is given by (25).

$$\overline{T}^* = \frac{1}{n}\sum_{j=1}^{n}\left(t_{2j+1} - t_{2j-1}\right) = \frac{t_{2n+1} - t_1}{n} \quad \ldots\ldots\ldots\ldots (23)$$

$$\overline{\overline{T}} = \frac{1}{n}\sum_{j=1}^{n}\left(t_{2j} - t_{2j-2}\right) = \frac{t_{2n} - t_0}{n} \quad \ldots\ldots\ldots\ldots (24)$$

$$\overline{T}^* = \overline{\overline{T}} + \frac{t_{2n+1} - t_{2n}}{n} - \frac{t_1 - t_0}{n} \quad \ldots\ldots\ldots\ldots (25)$$

In Figure 1 the number of zero up-crosses from t_0 to t_{26} is 13. The number of complete oscillations between positive amplitude values as the record goes from t_1 to t_{27} is 13. The computations given by (25) then show that $\overline{T}^*$ is equal to $\overline{\overline{T}}$ with the addition of two correction terms. The time from t_{26} to t_{27} divided by 13 would be added, and the time from t_0 to t_1 divided by 13 would be subtracted in order to compute $\overline{T}^*$ from $\overline{\overline{T}}$. In a very long wave record, these two correction terms of opposite sign become smaller and smaller. Hence for a long enough wave record, $\overline{T}^*$ can be made to equal $\overline{\overline{T}}$ to any desired degree of accuracy.

Relation to stop-watch observations--This result shows, therefore, that the formulas due to Rice give theoretical results which can be measured with a stop watch in terms of $\overline{T}^*$ to find the average 'period' of the waves. The visual observations reported in the past which yield the average of the time intervals between the successive crests of the waves as they pass a fixed point are therefore related to the expected number of zeros in terms of the theoretical power spectrum derived by Neumann. $\bar{\bar{T}}$ is the value, then, which would be reported visually in any wave system for a fully developed sea if the spectrum of Neumann is the spectrum which is present. $\bar{\bar{T}}$ is therefore given by (19) and the ratio of the wave crest 'speed' computed from $\bar{\bar{T}}$ to the wind velocity is therefore 0.866 in a fully developed sea.

The result is then that the average observed 'period' is much lower than the period at which the energy is a maximum in the spectrum. This is not too difficult to understand because heights are not associated with the various time intervals and because a time interval of ten seconds between successive crests has much more chance of occurring during a given length of observation than a time interval of 20 sec, simply because it takes a time interval of 20 sec longer to happen. The visual observation procedure therefore tends to overemphasize the low 'period' values and slight the high 'period' values so that the average of all these numbers is a number which is quite low in relation to the value of the period which contains the maximum energy of the spectrum.

An objection can be raised at this point to such a definition. If a minor ripple occurs on the sea surface near a value of zero for the record, then a very small low 'period' wave would occur, and a few of these in the record would tend to make $\bar{\bar{T}}$ smaller. It might be argued that a visual observation would tend to ignore such low 'period' fluctuations and concentrate on values which might be considered to be more representative. The effect is to increase $\bar{\bar{T}}$ only slightly since the probability of a ripple occurring right at the value of sea level is very small. The objection should not be considered important since the theoretical record in Figure 1 shows that ripples which are not near zero do not affect the value of $\bar{\bar{T}}$.

Another objection might be that this definition is not equivalent to the significant 'period' as defined by SVERDRUP and MUNK [1947] and by other workers in the field of ocean waves. The significant 'period' is defined to be the average value of the time intervals between the crests of the one-third highest waves. The significant 'period' does not have an easy interpretation in terms of the energy spectrum method of approach. Just why more significance should be attributed to the time interval between the crests of the one-third highest waves is a very important question; in fact, it has yet to be shown that there is anything particularly significant about the significant 'period.' It is strongly suspected that most wave 'periods' reported in the literature are related to $\bar{\bar{T}}$ and that the difference between $\bar{\bar{T}}$ and the significant 'period' is very small.

The value $\bar{\bar{T}}$ is thus quite likely to be the value reported in a visual observation if the sea is fully developed, and if the theoretical spectrum is correct it is given by (18). The spectrum for a sea which is not fully developed or for a swell would not be the same as the spectrum of a fully developed sea, and $\bar{\bar{T}}$ would not be represented by this particular formula.

Similar arguments show that the average time interval between the maxima is given by (21) and that there are 73 pct more maxima than waves in a sea. The record in Figure 1 shows ten relative maxima which are not at the same time wave crests in a record in which there are a total of 24 relative maxima. The record looks quite natural because of the extra oscillations which are imposed on the more dominant waves and there actually are 73 pct more maxima according to this definition in the record than there are waves. Thus if Neumann's theoretical spectrum is correct, statement III has been proved.

Wave length--In a simple harmonic progressive wave as represented by (3) and (4), there is no difficulty in defining what is meant by a wave length and in going theoretically from a function of time at a fixed point to a function of space along some line in the x,y plane at an instant of time. For the actual sea surface, this is not the case because the sea surface is the superposition of an infinite sum of infinitesimally high simple sine waves combined in random phase and traveling in different directions. The problem is not simple, and it is necessary to investigate this pattern in great detail.

As shown by PIERSON [1952], a realistic representation of the actual sea surface is given by

$$\eta(x,y,t) = \int_0^\infty \int_{-\pi/2}^{\pi/2} \cos\left(\frac{\mu^2}{g}(x\cos\theta + y\sin\theta) - \mu t + \psi(\mu,\theta)\right)\sqrt{[A(\mu,\theta)]^2\, d\theta\, d\mu} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (26)$$

Eq. (26) can be represented by a partial sum similar to the way in which (5) was represented except that a net over both the μ direction and the θ direction is needed. The function $\psi(\mu, \theta)$ is to be chosen in random phase just as before. The result is a short-crested Gaussian sea surface which has the property that it has the same energy spectrum of the function of μ when observed at any fixed point (x, y) as a function of time. The spectrum as a function of μ is found from the spectrum as a function of μ and θ by integrating the spectrum over θ.

The spectrum derived by Neumann does not treat the short-crestedness of the sea surface. It is not a function of the variable θ. The spectral components which go to make up the sea surface travel in different directions. When the sea surface is observed along the line given by the x axis of the x,y coordinate system, many of the waves of the sum which make up the total disturbance will be traveling in directions not corresponding to $\theta = 0$.

If the work of ARTHUR [1949] is used to suggest a possible form of the variation with respect to θ of the spectrum, the result is (27). The same relative height amplitudes as found by Arthur will occur at points outside of a storm with this spectrum. This representation has many features which would seem to be verified by theoretical investigations. Note that the integral from 0 to ∞ over μ, and from $-\pi/2$ to $\pi/2$ over θ of this function yields again the same value as the integral from 0 to ∞ of (15) as given originally by Neumann. The wind velocity vector is assumed to be pointed along the positive x axis.

It is necessary to consider the effect of waves traveling in different directions in the short-crested sea surface. In (27) the spectrum is symmetrical about $\theta = 0$, and the apparent crests on the sea surface will then appear to be traveling toward the positive x direction on the average. Then if a line parallel to the x axis is laid out on the sea surface, and if the waves along that line are evaluated, those elemental wave components which are traveling at an angle to the x axis produce a larger wave length (or a smaller wave frequency) on the x axis. The spectrum of the wave frequencies along the x axis is then given by (28), where a transformation is involved which corrects for the effect of projection and gives the apparent wave frequency in the desired direction.

$$[A(\mu,\theta)]^2 = \frac{2C}{\pi\mu^6} e^{-2g^2/v^2\mu^2}(\cos\theta)^2 \ldots\ldots\ldots\ldots (27)$$

for $-\pi/2 < \theta < \pi/2$ and zero otherwise.

$$[A(\nu_0)]^2 d\nu_0 = \int_{-\pi/2}^{\pi/2} \left[A_2\left(\left(\frac{g\nu_0}{\cos\theta_0}\right)^{\frac{1}{2}}, \theta_0\right)\right]^2 \frac{1}{2}\left(\frac{g}{\cos\theta_0\,\nu_0}\right)^{\frac{1}{2}} d\theta_0\, d\nu_0 \ldots\ldots (28)$$

$$[A(\nu_0)]^2 = \int_{-\pi/2}^{\pi/2} \frac{C}{\pi}\frac{(\cos\theta_0)^{9/2}}{g^{5/2}\nu_0^{7/2}} e^{-\frac{2g\cos\theta_0}{v^2\nu_0}}\, d\theta_0 \ldots\ldots\ldots (29)$$

When the results of (28) are used with (27), (29) which gives the spectrum of the apparent wave frequencies in terms of ν_0, for the particular case in which the function is observed along the x axis, is obtained. Eq. (29) should be integrated over θ_0, but it is more convenient just to indicate this symbolically and delay the actual integration to a later time.

Under these conditions the sea surface as a function of x at a fixed time can then be represented by (30) where $[A(\nu_0)]^2$ is the spectrum defined by (29). The whole procedure repeats itself in the computation of the average distance between the successive crests as a function of x. Eq. (31) is immediately noticed to be similar to previous equations such as (16), and when the substitution of (29) is made and the various integrals are evaluated the result is (32).

$$\eta(x) = \int_0^\infty \cos(\nu_0 x + \psi(\nu_0))\sqrt{[A(\nu_0)]^2 d\nu_0} \ldots\ldots\ldots\ldots (30)$$

$$\bar{f}_{\nu_0} = \left[\frac{\int_0^\infty f_{\nu_0}^2 [A(f_{\nu_0}]^2 \, df_{\nu_0}}{\int_0^\infty [A(f_{\nu_0}]^2 \, df_{\nu_0}} \right]^{\frac{1}{2}} \quad \text{. . . . . (31)}$$

$$\overset{\approx}{L}_0 = \frac{2\pi}{2} \frac{v^2}{g} \quad \text{. . . . . (32)}$$

The integration of (31) is not too difficult, and it suffices to interchange the order of integration as given in (29) and (31); that is, integrate the spectrum first with respect to f_{ν_0} and then with respect to θ_0, and the evaluation then is easy.

The result is (32) for $\overset{\approx}{L}_0$, which is the average distance between the crests on the surface of a short-crested sea as measured at a fixed time as a function of distance. When the results obtained for $\overset{\approx}{T}$, namely (18), are substituted into (32), the result is

$$\overset{\approx}{L}_0 = \frac{2}{3} \frac{g\overset{\approx}{T}^2}{2\pi} \quad \text{. . . . . (33)}$$

Eq. (33) states that the average distance between the successive dominant crests of the sea surface when observed at a fixed time as a function of space is equal to two-thirds of the value computed from the classical formula when the average time interval between successive crests at a fixed point is used as the 'period.' Thus if the theoretical spectrum obtained by Neumann is correct and if the effect of θ variability as assumed is correct, statement II has been proved. Verbal communication with Donald F. Bridenstine of the U. S. Coast Guard Search and Rescue Section in New York and recent work of DEARDUFF [1953] both suggest that this result is more nearly correct than that obtained without the two-thirds factor.

Wave instability--In working with the function of time above, it was also possible to compute the average number of maxima in a wave record as observed at a fixed point. The result was that there were 73 pct more such maxima. The same formulas apply as a function of space as observed at a fixed time, and it would now be desirable to compute the average number of maxima which would lie along the line $x = 0$ as a function of space. If an attempt is made to do this, it is found that the numerator of the expression involves the term $(f_{\nu_0})^{1/2}$. This means that the integral from 0 to ∞ does not exist since the exponential part becomes essentially unity for large values of f_{ν_0}. Therefore, there is no analogous value for the number of maxima as a function of x as observed at an instant of time. The value of the expression is infinite, which means that the sea surface is completely covered by very small maxima if Neumann's theoretical spectrum is true.

The sea surface in a fully developed sea is completely covered by ripples. The reason the sea is fully developed appears to be simply that no more energy can possibly be added at any frequency in the spectrum which can accept energy from the winds and that the rate of dissipation of energy due to breaking at all frequencies just balances the rate of addition of energy from the wind. In a fully developed sea, waves of all sizes are continuously breaking.

It would also appear from the results of Neumann that the wind cannot add energy at frequencies much less than the value where the maximum of the spectrum occurs and that the wind cannot add energy at values corresponding to wave frequencies associated with a group velocity equal to the wind velocity.

The above results imply that the formulas used above fail at the capillary level and that more refined investigations are needed at the very high frequency end of the spectrum. However, they do suggest also very strongly that the mechanism which prohibits the further growth of waves is a mechanism of continued breaking at the crests in a random statistical sense. If the theoretical spectrum derived by Neumann is correct, statement IV has therefore been proved.

Note that, if the effects of decrease of motion with depth are taken into consideration and the pressure at some depth below the sea surface is studied, these formulas would again have a meaning since the divergence of the integrals involved in computing the average number of maxima in the record as a function of space is counteracted as soon as the exponential damping of the high-frequency components is taken into consideration.

'Period' increase of ocean swell--It is now possible to give a consistent and logical explanation for the period increase of ocean swell without recourse to any kind of dissipation of the high-frequency (or the low-period) components. The puzzle to oceanographers for a great many years has been the observed fact that the average time interval between the crests of waves observed in the generating area is considerably lower than the average time interval between the crests of the highest swell observed outside of the generating area. Stated another way, when the highest swell is passing, its average 'period' is greater than the average 'period' in the storm.

Consider a storm, therefore, with a spectrum in the storm given by (27). Also suppose that the storm has a fetch of length F, a duration of time D_s, after the waves have been fully generated, that the storm has a width W_s, and that the storm is being observed at a point R units away at a time t_{ob}. Let x and y stand for the Cartesian coordinates of these points outside the storm where the center of the forward edge of the storm is the origin of the Cartesian coordinate system and where x is the distance measured away from the storm in the direction in which the winds are blowing in the storm. The symbol R equals $\sqrt{x^2 + y^2}$ in this coordinate system. The time t_{ob} is measured with reference to the time that the storm reaches full development, and the waves at the forward edges of the storm are first represented by (27).

Then at some number of hours later at a given distance away from the forward edge of the storm, the various spectral components in the spectrum at the source begin to arrive. If the spectrum for the swell is to be forecast, it is simply necessary to apply (34). The spectrum of the sea in the storm is multiplied by one if the value of μ lies between the two inequalities indicated and if the value of θ lies between the two inequalities indicated. The spectrum of the swell is zero otherwise. (For further information on this filtering action, see PIERSON [1952] and PIERSON, NEUMANN, and JAMES [1953].)

$$\left.\begin{aligned} \frac{g(t_{ob}-D_s)}{2(R+F)} \le \mu \le \frac{g t_{ob}}{2R} \\ \tan^{-1}\left(\frac{y-\frac{W_s}{2}}{x}\right) \le \theta \le \tan^{-1}\left(\frac{y+\frac{W_s}{2}}{x}\right) \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (34)$$

The result is that only a narrow band of spectral frequencies and directions is present at a point of observation at a distance outside the storm. As time increases, at this point of observation, this band of frequencies tunes through the spectrum of the waves as given at the source, starting with the low-frequency values, increasing to the medium values, and finally going to the high-frequency values.

With a narrow band of frequencies present, the observed average 'period' will be very nearly equal to the frequency at the middle of the band. In the storm area, the average 'period' $\bar{\bar{T}}$ is observed, and it is given by 0.866 × $2\pi v/g$. Outside the storm, the waves will be highest when the spectrum has the most energy. This occurs when the band pass filter is tuning through the value at which the spectrum is a maximum at a function of frequency. The waves will therefore be highest when the frequencies present bracket the value of μ_{max} as given by (11). The value of the 'period' of the swell is therefore given by 1.22 × $2\pi v/g$. Thus in the storm a low 'period' is observed owing to the peculiarities of the technique of observation, and outside the storm a high 'period' is observed which was really there all the time. The ratio of $\bar{\bar{T}}_D$ (which is the 'period' of the highest waves outside of the generating area) to $\bar{\bar{T}}_F$ (which is the 'period' inside the generating area) as given in (12) must therefore be equal to the ratio of T_{max} to $\bar{\bar{T}}$, and this in turn is equal to $\sqrt{2}$ as was shown by (19).

This means that the 'period' of the highest waves outside of the generating area can never exceed the 'period' of the waves inside of the generating area by more than a factor of $\sqrt{2}$. If the 'period' in the storm is ten seconds, the 'period' of the highest waves outside the storm, no matter how great the decay distance, can never exceed 14.14 sec. If the theoretical spectrum derived by Neumann is correct, statement I has now been proved.

This result is in sharp contrast with the theoretical results of MUNK and ARTHUR [1951] and BRETSCHNEIDER [1952]. It seems to be far more realistic in that a continuously increasing 'period' implies energy in the wave spectrum at all low frequencies.

The filter given by (34) appears to account for the entire decrease of wave height outside the generating area. Eddy friction, or viscosity, does not appear to be important.

Summary and conclusions--This paper has presented many new developments in the interpretation of the actual appearance of the sea surface. It answers the question, What do we really see when we see the sea? What we see has nothing to do with the properties of a simple harmonic progressive wave and with the incorrect application of rather simple averaging techniques in order to force the irregular sea surface into a pattern like that of a simple harmonic progressive wave. The classical formulas which were derived for simple harmonic progressive waves do not really hold for actual waves. They are not valid for the irregular pattern which represents the fully developed sea.

The results which have been obtained, as far as the exact numerical values, depend upon the theoretical spectrum derived by NEUMANN [1953]. The values would be different if the spectrum were different, but the principles employed would remain the same.

When considered all together, these results serve as an important independent argument that the results of Neumann, when combined with the theory of a quasi-stationary Gaussian process, yield properties which represent ocean waves in the most realistic way yet achieved theoretically.

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THE USE OF A FILTER TO SORT OUT DIRECTIONS IN A SHORT-CRESTED GAUSSIAN SEA SURFACE

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Abstract--The method of stereo pairs may be used to obtain wave records which characterize the sea surface completely at any given place. The three-dimensional aerial photograph thus obtained is divided into 2N + 1 wave records spaced Δy ft apart. The 2N + 1 wave records are combined statistically into one wave record, and the energy spectrum for spectral components within a certain angular band is then computed. A filter function which depends on N and Δy is derived from the averaging process. The filter function operates on the energy spectrum in such a way that, for proper choice of N and Δy, the waves whose spectral directions are any other than that which is desired are eliminated. The energy spectrum which results is composed of the energy of those waves which travel in the desired direction. A sample example illustrates this process.

Introduction--The sea surface is believed to be made up of a sum of an infinite number of infinitesimally high sine waves traveling in different directions with different frequencies added together in random phase [PIERSON, 1952]. This surface, at any point, has a certain amount of energy associated with it, and this energy is distributed among the component waves according to frequency and direction. It is this distribution of energy and the particular direction of travel of each of the component waves which defines the two-dimensional energy spectrum $[A_2(\mu, \theta)]^2$, where $\mu = 2\pi/T$ is the spectral frequency and θ is the direction of propagation. This is the property of the ocean surface which must be measured.

The mathematical expression which appears best to characterize this sea surface is

$$\eta(x,y,t) = \int_0^\infty \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \cos\left[\frac{\mu^2}{g}(x\cos\theta + y\sin\theta) - \mu t + \psi(\mu,\theta)\right] \sqrt{\left[A_2(\mu,\theta)\right]^2 d\theta\, d\mu} \quad \ldots\ldots\ (1)$$

This is the Gaussian case of the Lebesgue energy integral for short-crested wave systems, where the elevation of the free surface at any point and time is a function of the energy spectrum $[A_2(\mu, \theta)]^2$, the spectral frequency $\mu = 2\pi/T$, gravity g, direction θ, space coordinates x and y, time t, and an arbitrary term which assigns the phases $[\psi(\mu, \theta)]$.

It is possible to rewrite (1) as a limit of partial sums if a network is constructed over the μ, θ coordinate system and the mesh of the network is allowed to go to zero. The result is

$$\eta(x,y,t) = \lim_{\substack{\mu_{2S}\to\infty \\ R\to\infty \\ \mu_{2n+2}-\mu_{2n}\to 0 \\ \theta_{2r+2}-\theta_{2r}\to 0}} \sum_{n=0}^{S}\sum_{r=0}^{R} \sqrt{\left[A_2(\mu_{2n+1},\theta_{2r+1})\right]^2(\mu_{2n+2}-\mu_{2n})(\theta_{2r+2}-\theta_{2r})}\, \cos\left[\frac{\mu_{2n+1}^2}{g}(x\cos\theta_{2r+1} + y\sin\theta_{2r+1}) - \mu_{2n+1}t + \psi(\mu_{2n+1},\theta_{2r+1})\right] \quad \ldots\ldots\ (2)$$

In order to compute $[A_2(\mu, \theta)]^2$, it is first necessary to obtain a wave record which describes the short-crestedness of the sea surface in the area of interest. Since one problem of importance is to forecast the propagation of waves out of a generating area, it would be best to make the observations at the edge of the storm over an area where the sea is fully developed. In addition, if a record is to fulfill all the requirements requested of it, there must be some mechanism which yields information about the direction of travel of the spectral components, so that the complete form of the two-dimensional energy spectrum can be computed.

The problem therefore resolves itself into two distinct parts: (1) What is the best way to record ocean waves at the edge of a wave generating area, on the shortest notice, that will yield information about the distribution of energy among the spectral components according to frequency and direction? (2) What is the best method of analysis of this wave record?

Energy spectra as a function of frequency alone have been computed from available wave records [PIERSON and MARKS, 1952], and theoretical calculations have been made which describe the state of the sea at various times and places with respect to the distribution of energy among the spectral frequencies, but little has been done about the distribution over θ. In lieu of actual wave records from a wave-generating area at sea, energy spectra have been assumed at the edge of such an area of regular shape [PIERSON, 1952]. NEUMANN [1953] has derived theoretical wave spectra as a function of μ and the wind velocity. Theoretical results have explained many features of the sea surface such as the narrowing of the frequency band width with distance from the storm, the distribution of energy at a given time and place, the decrease in wave height with distance, the increase in the period of swell, and other features which have and have not been observed [PIERSON, 1952].

Since no actual wave records have ever been obtained at the edge of a generating area to corroborate the far-reaching implications of the theory and to determine the exact form of $[A_2(\mu,\theta)]^2$, it seems apparent that such wave records should be obtained as soon as possible.

High-altitude stereo photography--High-altitude stereo photography appears to be the best method available to determine the two-dimensional energy spectrum of the sea surface at the edge of a storm. Two photographs, made at a safe height, reduce the danger involved in making the records. In addition, the photographs obtained in this manner will eliminate the necessity for making many runs over the sea surface as would, for example, be required by an altimeter type of wave recorder. This cuts down the time required for making the observations. The sea surface may be divided up into as many runs as desired and the records may be arranged in any pattern. A typical pattern of runs and a grid system are shown in Figure 1. This method has all the desired properties which were outlined in the introduction. The wave spectrum as a function of both μ and θ can be determined from the stereo aerial photographs. It is necessary to know the wind direction. A wave record as a function of time at a fixed point would be useful as a check of the results, but it would not be essential.

An alternate method has been described [PIERSON, 1952] on the basis of airborne recording. For a fixed direction θ^*, the sea surface can be recorded as a function of distance along the line of flight x'. In addition, the free surface as a function of time can be recorded. Both of these functions are examples of stationary series, and both may be analyzed by the methods described in the literature [TUKEY, 1949; TUKEY and HAMMING, 1949]. Many different values of θ^* can be chosen and a whole set of functions for different θ^* can be found. It is necessary to determine $[A_2(\mu,\theta)]^2$ from the stationary series thus observed. Pierson found that seven analyses of the form described by TUKEY and HAMMING [1949] would have to be carried out. The result would be 77 linear inhomogeneous equations with 77 unknowns which would need to be solved. This represents an immense amount of work and it is enough to make an easier method worth seeking.

A theoretical discussion of a sample case will illustrate the usefulness of stereo pairs in power spectrum analysis.

Method of observation--A camera with a wide-angle lens, say 90°, can take a picture the dimensions of which are twice the height of the plane. For example, at 5000 ft a sea composed entirely of waves with 20-sec period will yield a photograph which contains approximately 4.91 waves, equivalent to a wave record 1.64 min long. On the other hand, a sea composed entirely of three-second waves would result in a photograph which contains 208.15 waves, the equivalent of a wave record 10.41 min long. Since the sea at the edge of the storm has a wide band of spectral components, the range of wave periods recorded would probably include all periods from three to 20 sec, so that a photograph taken at 5000 ft would more likely yield a photograph equivalent to about six or seven minutes of wave record.

It is necessary to compute the energy spectrum at the edge of the generating area. Therefore, a point on the leading edge, which is free from angular spreading, should be selected as the place to take the stereo photographs. Once the place to be photographed is chosen, the weather conditions will determine whether it is feasible to make observations and at which height the observations should be made.

Theoretical discussion of power spectrum analysis of stereo pairs--A photograph might be divided up into a grid of points (Fig. 1). Since one pair of photographs is not equivalent to 20 min

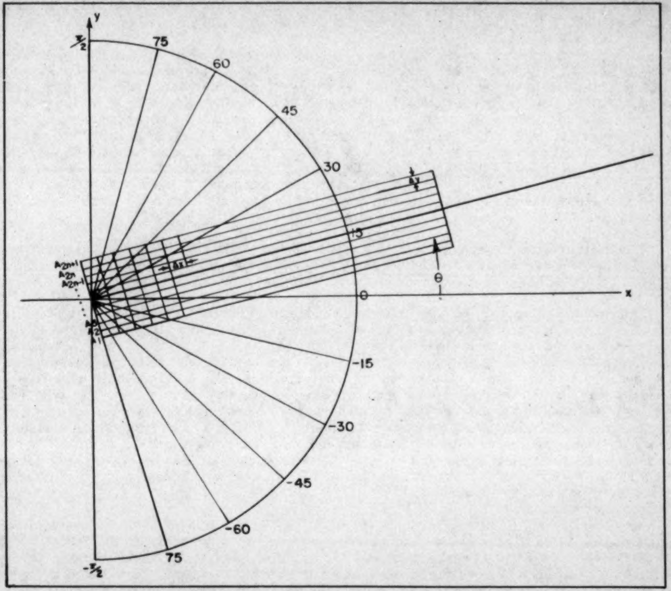

Fig. 1--Diagram of runs to be marked off on stereo photographs; the x-axis is parallel to the dominant direction of the crests; the grid system is arranged for θ = 15°

of wave record (the desired length of record due to compromise between a small loss in accuracy and a large saving in computational labor), several pictures of the 'same' sea surface may be taken and spliced by statistical methods. (As long as the waves retain their basic features and the statistical properties of the sea surface remain constant during the photographing process, the records obtained will all have the same properties and can be analyzed in the same manner.) The grid contains 2N + 1 horizontal rows of points spaced Δy ft apart. The points on each row, spaced Δx ft apart, are read off the photograph directly as heights above an arbitrary datum plane situated below the lowest trough. Each column is averaged, and the result is one wave record where the points are the average values of the columns A, B, C . . . The statistical methods of TUKEY [1949] and TUKEY and HAMMING [1949] which describe the computation of energy spectra, in communication theory, have been adopted for ocean waves [PIERSON, 1952; PIERSON and MARKS, 1952]. From the averaged wave record, the energy spectrum can be computed.

Derivation of theory--If the cosine term in (2) is expanded trigonometrically the result is

$$\eta(x,y,t) = \lim_{\substack{\mu_{2S}\to\infty \\ R\to\infty \\ \mu_{2n+2}-\mu_{2n}\to 0 \\ \theta_{2r+2}-\theta_{2r}\to 0}} \sum_{n=0}^{S}\sum_{r=0}^{R} \sqrt{\left[A_2(\mu_{2n+1},\theta_{2r+1})\right]^2(\mu_{2n+2}-\mu_{2n})(\theta_{2r+2}-\theta_{2r})}\left\{\cos\left[\frac{\mu_{2n+1}^2}{g}y\sin\theta_{2r+1}\right]\cos\left[\frac{\mu_{2n+1}^2}{g}\right.\right.$$

$$\left.\cdot\, x\cos\theta_{2r+1}-\mu_{2n+1}t+\psi(\mu_{2n+1},\theta_{2r+1})\right]-\sin\left[\frac{\mu_{2n+1}^2}{g}y\sin\theta_{2r+1}\right]$$

$$\left.\cdot\,\sin\left[\frac{\mu_{2n+1}^2}{g}x\cos\theta_{2r+1}-\mu_{2n+1}t+\psi(\mu_{2n+1},\theta_{2r+1})\right]\right\} \quad \ldots\ldots\ldots\ldots\ldots (3)$$

If the 2N + 1 wave records, spaced Δy ft apart, are averaged over y point for point, the wave record thus obtained may be written as

$$\frac{1}{2N+1}\sum_{j=-N}^{+N}\eta(x,y+j\Delta y,t)\cong\sum_{n=0}^{S}\sum_{r=0}^{R}\sqrt{\Big[A_2(\mu_{2n+1},\theta_{2r+1})\Big]^2(\mu_{2n+2}-\mu_{2n})(\theta_{2r+2}-\theta_{2r})}\,\frac{1}{2N+1}\Bigg\{1+ 2\sum_{j=1}^{N}\cos\Big[\frac{\mu_{2n+1}^2}{g}(j\Delta y\sin\theta_{2r+1})\Big]\cos\Big[\frac{\mu_{2n+1}^2}{g}x\cos\theta_{2r+1}-\mu_{2n+1}t+\psi\Big]\Bigg\}\quad\text{. . . . . (4)}$$

where the sine terms drop out because they are equal in magnitude and opposite in sign. As $\mu_{2n+2}-\mu_{2n}\rightarrow 0$ and $\theta_{2r+2}-\theta_{2r}\rightarrow 0$, the partial sum in (3) is, for all purposes, indistinguishable from the sea surface it represents. Therefore, the limit in (3) may be dropped.

The coefficient of the cosine term in (4) is expanded and the collected terms are substituted back into the equation. The result is

$$\bar{\eta}(x)\cong\sum_{n=0}^{S}\sum_{r=0}^{R}\sqrt{\Big[A_2(\mu_{2n+1},\theta_{2r+1})\Big]^2(\mu_{2n+2}-\mu_{2n})(\theta_{2r+2}-\theta_{2r})}\;\left[\frac{\sin\Big[\frac{\mu_{2n+1}^2}{g}(\Delta y\sin\theta_{2r+1})(N-\frac{1}{2})\Big]}{(2N+1)\sin\Big[\frac{1}{2}\frac{\mu_{2n+1}^2}{g}\Delta y\sin\theta_{2r+1}\Big]}\right] \cdot\cos\Big[\frac{\mu_{2n+1}^2}{g}x\cos\theta_{2r+1}-\mu_{2n+1}t+\psi(\mu_{2n+1},\theta_{2r+1})\Big]\quad\text{. . . . . (5)}$$

The averaged record can also be represented as

$$\bar{\eta}(x)=\int_0^\infty\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\sqrt{\Big[A_2(\mu,\theta)\Big]^2\left[\frac{\sin\Big[\frac{\mu^2}{g}(N-\frac{1}{2})\Delta y\sin\theta\Big]}{(2N+1)\sin\Big[\frac{1}{2}\frac{\mu^2}{g}\Delta y\sin\theta\Big]}\right]^2 d\mu\, d\theta}\;\cos\Big[\frac{\mu^2}{g}x\cos\theta-\mu t+\psi(\mu,\theta)\Big]\quad\text{. . . . . . (6)}$$

where the notation reverts again to the integral form and the complete coefficient of the cosine term is brought under the radical sign.

Since the record is made at an instant of time, a transformation is made to a space coordinate system. The transformation is

$$\left.\begin{array}{l}\nu_0=\dfrac{\mu^2}{g}\cos\theta\\[2ex] \theta_0=\theta\end{array}\right\}\quad\text{. . . . . (7)}$$

where ν_0 is the observed spectral wave number and θ_0 measures angular direction when once the coordinate axes are chosen with respect to the selected runs.

From (7) it is seen that

$$\int_0^\infty\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\Big[A_2(\mu,\theta)\Big]^2 d\theta\, d\mu=\int_0^\infty\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\Big[A_2\Big(\Big[\frac{g\nu_0}{\cos\theta_0}\Big]^{\frac{1}{2}}\theta_0\Big)\Big]^2\frac{1}{2}\Big(\frac{g}{\nu_0\cos\theta_0}\Big)^{\frac{1}{2}}d\theta_0\, d\nu_0\quad\text{. . . . . . (8)}$$

The integral of the right-hand side over the θ_0 coordinate is

$$\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\Big[A_2\Big[\Big(\frac{g\nu_0}{\cos\theta_0}\Big)^{\frac{1}{2}}\ \theta_0\Big]\Big]^2\frac{1}{2}\Big(\frac{g}{\nu_0\cos\theta_0}\Big)^{\frac{1}{2}}d\theta_0=\Big[A_2(\nu_0)\Big]^2$$

Therefore under this transformation, (6) becomes

$$\eta(\bar{x})=\int_0^\infty \sqrt{\left[\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\left[A_2\left(\nu_0,\theta_0\right)\right]^2\left[\frac{\sin\left[\left(N-\frac{1}{2}\right)\Delta y\,\nu_0\tan\theta_0\right]}{(2N+1)\sin\left[\frac{1}{2}\Delta y\,\nu_0\tan\theta_0\right]}\right]^2 d\theta_0\right] d\nu_0}\cdot\cos\left[\nu_0 x+\psi(\nu_0)\right]\;\ldots\ldots (9)$$

where $[A_2(\nu_0, \theta_0)]^2$ is written instead of $[A_2(g\nu_0/\cos\theta_0)^{1/2}\theta_0)]^2$ for simplicity. Eq. (9) is a function of x alone and thus the series of points in the x direction as averaged over y can be analyzed for the spectrum as a function of ν_0 by the techniques given by PIERSON and MARKS [1952].

In (9), the energy spectrum $[A_2(\nu_0, \theta_0)]^2$ is multiplied by

$$\left[\frac{\sin\left[\left(N-\frac{1}{2}\right)\Delta y\,\nu_0\tan\theta_0\right]}{(2N+1)\sin\left[\frac{1}{2}\Delta y\,\nu_0\tan\theta_0\right]}\right]^2 \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

This serves to filter out those portions of the energy in the spectrum which travel in all directions except those within a small angular range about θ_0. By varying θ_0 in (10), the energy which travels in any desired direction can be found.

Properties of the filter--It is this filter as given by (10) which will now be investigated in detail. Some properties of this function are: (1) It is an even function of θ_0. (2) It is everywhere positive. (3) It has its greatest maximum at the origin of orientation and it damps out very rapidly with θ_0. (4) It becomes a low-oscillating function with several minor maxima before it reaches a major maximum again. An example of this appears in Figure 2. (5) The number of minor maxima varies directly as N. (6) The angular distance between the major maxima depends on Δy.

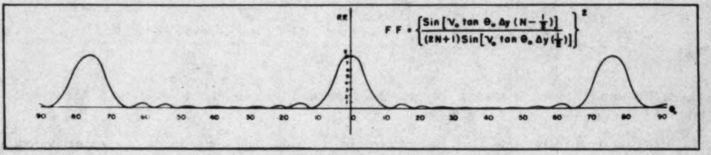

Fig. 2--Sample filter function for N = 10, Δy = 125 ft

In order to show how this filter function works, consider the particular filter illustrated in Figure 2. This function multiplies that portion of $[A_2(\nu_0, \theta_0)]^2$ between ± 10° by large values and the rest of the energy spectrum by very small values or zero up to 66° where another maximum occurs. If the value of $[A_2(\nu_0, \theta_0)]^2$ is small beyond $\theta_0 = \pm 66°$, then the result is a filtered energy spectrum which contains only the energy which travels between $\theta_0 = \pm 10°$, appropriate to the particular wave number ν_0. This same procedure may be used for all the ν_0, and the result is the distribution of energy among the ν_0 which travels in a certain θ_0 band-width only. In other words, the energy spectrum has been filtered to allow only energy which travels nearly in the $\theta_0 = 0$ direction to be shown and all the energy which travels in other directions is suppressed.

The energy spectrum is the same at any point in the 'same' sea. Let the coordinate axes (ν_0, θ_0) be set with respect to the energy spectrum and if $[A_2(\nu_0, \theta_0)]^2$ is multiplied by the filter function for $\theta_0 = 0$ throughout, then the energy which travels in this direction is determined. If θ_0 remains equal to zero in $[A_2(\nu_0, \theta_0)]^2$ but is varied in (10) then this is the same as turning the filter to a new direction. That is, if $\theta_0 = 0$ in $[A_2(\nu_0, \theta_0)]^2$ and if $\theta_0 = 30°$ in (8), then the energy which travels in the direction 30° to the original orientation is found. Consequently, it is also possible to focus the filter function in any direction so that only the energy traveling in that direction is evident. This is accomplished in practice by turning the grid system in Figure 1 through a given angular range in the stereo photographs. Also the θ_0 band-width, through which the energy travels, may be regulated. Since N determines the θ_0 band-width, the smaller the energy passage is made, the greater N becomes and therefore the more computational work must be done. Also Δy determines the place where the secondary maxima appear. When Δy is made larger, the secondary maxima are displaced further. However, there must be 2NΔy ft of width on the photograph to allow for the 2N+1 wave records. Therefore, it is necessary that N and Δy be carefully selected to (1) provide a small angular band-width through which the energy travels; (2) displace the secondary maxima far enough to make their effect negligible; (3) minimize computation; and (4) make the aerial photography practical.

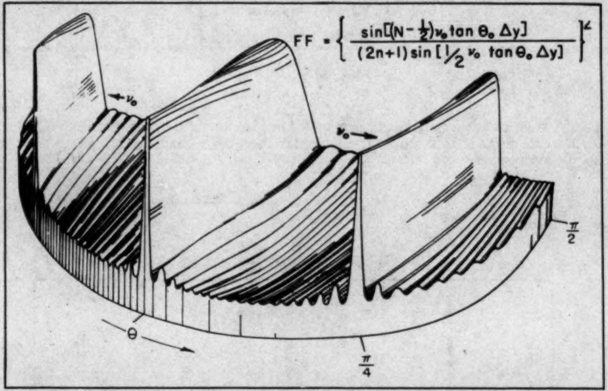

Fig. 3--Three-dimensional view of the filter function for N = 10, Δy = 125 ft

Figure 3 shows a three-dimensional view of a typical filter function. The filter has a high ridge in the center which is constant in amplitude but variable in width. For large ν_0 (small period), the width of the filter is small. As ν_0 becomes smaller, the width of the filter becomes larger. This means, for example, that for four-second waves, the filter might allow all the energy from these waves in an angular range of 10° to pass through, while the energy in waves with 20-sec periods might pass through a band-width of, say, 30°. Therefore, the filter is more reliable for low-period waves than for high-period waves. The same holds true for the series of smaller ridges which flank the larger ridge. The contribution of all the smaller ridges is very small compared to that of the large ridge. (This will be discussed.) On the wings of the figure appear a pair of high ridges which have the same amplitude as the ridge in the center of the figure. These flanking ridges are always kept in such a position that they multiply portions of the energy spectrum which are nearly zero. Therefore, the contribution from the pair of flanking high ridges is negligible.

A sample example--At this time, no stereo pairs have been made and analyzed. Instead, a theoretical energy spectrum will be operated on by a filter with certain characteristics in order to demonstrate the properties discussed above.

The conditions imposed on the filtering process are that for waves with a ten-second period, the energy passing through must be confined to $\theta_0 = \pm 10°$ and also that no secondary maxima should appear before $\theta_0 = \pm 40°$. Investigation showed that N = 10 and Δy = 125 ft yielded the desired results. This filter is seen in Figure 3.

The two-dimensional theoretical energy spectrum is given by

$$\left.\begin{aligned} \left[A_2(\mu,\theta)\right]^2 &= \frac{c}{\mu^6} e^{-2g^2/v^2\mu^2} \cos^2\theta \qquad \text{if } -\frac{\pi}{2} < \theta < \frac{\pi}{2} \\ \left[A_2(\mu,\theta)\right]^2 &= 0 \qquad \text{otherwise} \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (11)$$

where v is the wind velocity and C is equal to 3.05×10^4 cm^2 sec^{-5}. It is assumed that all energy travels out of the generation area. The one-dimensional energy spectrum [NEUMANN, 1953] was modified by $(\cos\theta)^2$ on consideration of the results of ARTHUR [1949]. It is the best available estimate of the two-dimensional energy spectrum for a fully developed sea at a given wind velocity v. For different wind velocities, the spectrum will have different shapes. In the (ν_0, θ_0) coordinate system, the energy spectrum becomes

$$\left.\begin{aligned} \left[A_2(\nu_0,\theta_0)\right]^2 &= \frac{c(\cos\theta_0)^{9/2}}{2g^{5/2}\,\nu_0^{7/2}}\, e^{-2g\cos\theta_0/v^2\nu_0} && -\frac{\pi}{2} < \theta_0 < \frac{\pi}{2} \\ \left[A_2(\nu_0,\theta_0)\right]^2 &= 0 \quad \text{otherwise} \end{aligned}\right\} \qquad (12)$$

where the Jacobian is again included to preserve the mapping of the transformation and where θ_0 equals θ. For the purpose of this study, a value for the wind velocity of 35 knots was chosen and the constants were substituted in (10). The result is

$$\left[A_2(\nu_0,\theta_0)\right]^2 = \frac{C^*(\cos\theta_0)^{9/2}}{\nu_0^{7/2}}\, e^{-\frac{6.05\times10^{-4}\cos\theta_0}{\nu_0}} \qquad -\frac{\pi}{2} < \theta_0 < \frac{\pi}{2} \qquad (13)$$

Figure 4 shows a three-dimensional view of (13).

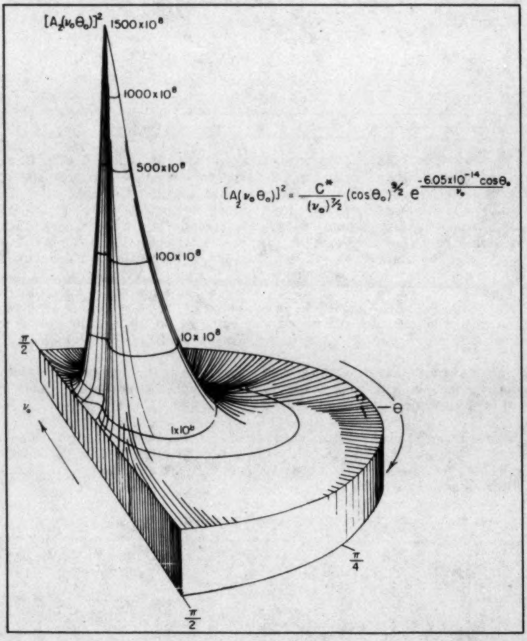

Fig. 4--Three-dimensional view of energy spectrum in the (ν_0, θ_0) coordinate system; the wind velocity is approximately 35 knots

The filtered energy spectrum is

$$FES = C^{*}\left[\frac{\sin\left[38\times10^{3}\nu_0\tan\theta_0\right]}{\sin\left[2\times10^{3}\nu_0\tan\theta_0\right]}\right]^{2}\frac{(\cos\theta_0)^{9/2}}{\nu_0^{7/2}}e^{-\frac{6.05\times10^{-4}\cos\theta_0}{\nu_0}} \quad \text{.........} \quad (14)$$

and a three-dimensional view of the filtered energy spectrum appears in Figure 5. This shows the amount of energy that travels in a band centered about the direction $\theta_0 = 0$.

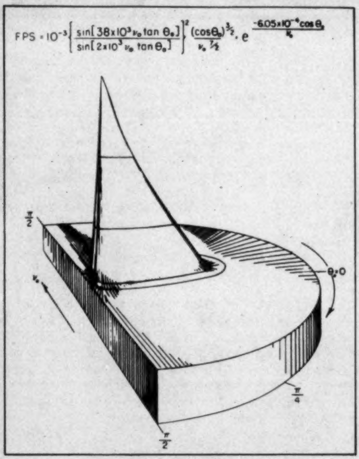

Fig. 5--Three-dimensional view of filtered energy spectrum; filter is oriented in direction of $\theta_0 = 0$

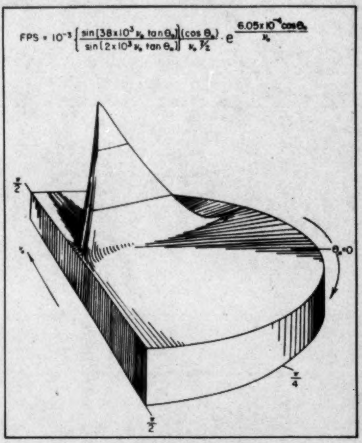

Fig. 6--Three-dimensional view of filtered energy spectrum; filter is oriented in direction of $\theta_0 = 10°$

If the energy that travels in a band centered about the direction $\theta_0 = 10°$ is desired, then the filter is turned 10° and the result is seen in Figure 6. The amount of energy is much less than that which travels in the direction $\theta_0 = 0°$. It is also expected that the energy should diminish to nearly zero as the filter is turned through 50 or 60°.

Some of the energy passes through the minor maxima, and this amount must be calculated to provide some limits of confidence in the results. Computations have shown that the effect of the minor maxima is 1.7 pct of the total effect of the filter function for the observed wave number appropriate to a period of four seconds. For smaller wave numbers (larger periods) the effect of the secondary maxima is less.

The record which is actually analyzed results in a spectrum which is a function of ν_0 alone as given by (9). It no longer shows any angular variation. The numerical analysis of the series of averaged points yields estimates of the energy in a series of ν_0 bands along the ν_0 frequency axis, just as the analysis of a record as a function of time yields estimates of the energy in a given ν_0 band.

For each ν_0 band the angular variation of the filter as shown in Figure 2 can be replaced by a rectangular filter with an equivalent area under it. The angular spread varies as a function of ν_0. The energy obtained in the numerical analysis can then be spread out over the θ_0 direction, and an estimate of the average value of $[A_2(\nu_0, \theta_0)]^2$ over a small part of the ν_0, θ_0 plane is thus obtained.

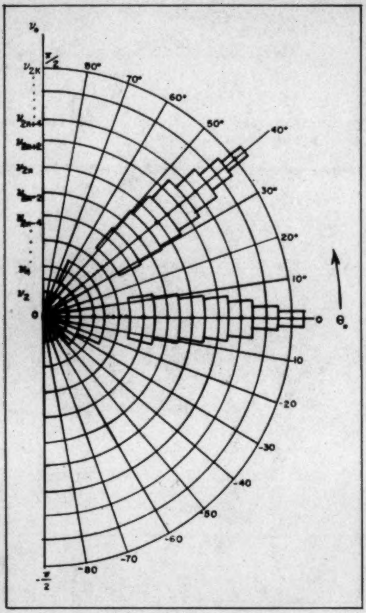

Fig. 7--Graphic illustration of the integration of the filtered energy spectrum over θ_o, for all ν_o

Figure 7 shows a series of such areas as they would be located in the ν_o, θ_o plane for a given numerical analysis. Figure 7 also shows the areas which would result upon turning the filter through 40°. The entire plane can thus be scanned by turning the filter, and the variation of $[A_2(\nu_o, \theta_o)]^2$ over the entire ν_o, θ_o plane can then be inferred. From this, the spectrum as a function of μ and θ can be computed, and the problem of determining the energy spectrum of the sea surface as a function of frequency and direction is solved.

Conclusion--It is believed that the method of stereo pairs is a practical way to obtain data which will permit the determination of the two-dimensional energy spectrum of an ocean wave system at the edge of a wave-generating area. The amounts of energy which travel in different directions may be sorted out with the aid of the derived filter function.

Since the fact that the wave spectrum is two dimensional affects the theory of wave propagation and of swell forecasting to a great extent, this paper points a way to the solution of this fundamental problem of wave theory.

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THE BLACK SEA: ENERGY BALANCE AND EVAPORATION

J. Neumann and N. Rosenan

Abstract--The energy equation is applied to data of four areas of the Black Sea. The data used are as follows: air temperature, pressure, and cloudiness (Landsberg's, 1945, bimonthly isopleths); humidity of air (estimates based on humidity data of coastal stations); sea-surface temperatures (observations by British ships); and sea-surface salinity (17 o/oo, Sverdrup and Others in 1946).

The results indicate an average annual evaporation of 110 cm, approximately. As in the corresponding latitudes of the oceans, evaporation decreases from south to north and from west to east. Evaporation during the autumn-winter semester considerably exceeds evaporation in the remaining semester.

The hydrologic balance determined by Sverdrup and Others for the Black Sea indicated an annual evaporation of 84 cm. It is suggested that the precipitation and runoff terms of that balance are larger to an extent needed to compensate for the larger value of evaporation derived from the energy balance.

The terms precipitation and runoff are subjected to a re-examination. The authors' estimate of annual precipitation is in close agreement with that given by Sverdrup (58 cm). By combining the figure for evaporation (energy balance) with the precipitation estimate and with data for the in- and outflow through the Bosporus, a runoff from the catchment to the sea amounting to 100 cm/year is required. Hydrographic data for the catchment available to the authors, first communicated by Russian authors after publication of Sverdrup's hydrologic balance for the sea, cover 92 pct of the catchment and account for a runoff of 91 cm/year. Thus, the evaporation figure derived from energy balance computations receives close support from hydrographic data.

Introduction--SVERDRUP and Others [1946, p. 650] have set up the hydrologic balance for the Black Sea as shown in Table 1.

Table 1--Hydrologic balance for the Black Sea

Gains	Amount	Losses	Amount
	m^3/sec		m^3/sec
Inflow through Bosporus	6,100	Outflow through Bosporus	12,600
Precipitation	7,600	Evaporation	11,500
Runoff	10,400		
	24,100		24,100

The figures for the in- and outflow through the Bosporus are based on the current measurements of Merz and have been accepted by both Sverdrup and WÜST [1952] as the best available values of these terms.

The value of evaporation obtained as the balance of gains over the outflow through the Bosporus is equivalent to an annual amount of 84 cm. Energy balance calculations for the corresponding latitudes of the Atlantic Ocean [JACOBS, 1942; SVERDRUP and Others, 1946] have also resulted in an annual evaporation of 84 cm. However, energy consideration applied to the conditions of the Black Sea suggest that the evaporation figure derived from the hydrologic balance sheet is far too low and, in consequence, at least one other term of the hydrologic balance requires re-examination. Consider, for example, conditions along the 43°N latitude which, roughly speaking, bisects the Black Sea. In the corresponding latitude of the Atlantic Ocean the average annual cloud amount is nearly seven-tenths; the range of annual variation is small, except near the coasts [U. S. WEATHER BUREAU, 1938]. In the case of the Black Sea, on the other hand, LANDSBERG's [1945] bimonthly maps of cloud amount indicate that the annual average of that element is between five- and six-tenths but rather nearer to five-tenths; the annual range is large. In summer, for instance, cloudiness is slightly less than four-tenths. In the circumstances, the amount of insolation reaching the Black Sea surface is bound to be considerably greater than for the Atlantic Ocean in the same latitude.

Detailed computations, using well-known empirical formulas, show that the net radiative balance for the Black Sea exceeds the parallel balance for the corresponding latitudes of the North Atlantic by approximately 23,000 gm cal/cm^2/year. It remains to consider, however, whether processes of energy advection by the in- and outflowing water masses could account for a reduction in the amount of heat available for evaporation. If it is shown for the Black Sea that horizontal advection of energy is insignificant, then we shall be justified in assuming that the major part of the above mentioned excess net radiative balance is transferred to the atmosphere in the form of latent heat, thus causing the Black Sea to have a larger evaporation than the corresponding latitudes of the Atlantic Ocean.

It may be easily shown that for the Black Sea as a whole, gains or losses of energy from horizontal advection are likely to be small. Runoff from the catchment to the sea, related to the surface area of the sea, is estimated at 100 cm/year (see Relation of the present results to hydrology of the sea below); further, Sverdrup's hydrologic balance, cited above, indicates that outflow from the Black Sea to the Mediterranean is also about 100 cm/year while the reverse flow is about half as great. To take an extreme case, we shall assume that all these processes entail an energy change of the same sign. We shall also assume that the energy loss is five gm cal of heat per gram of water advected. (It is believed that such an assumption is on the high rather than on the low side.) Under these assumptions, the energy loss would amount to 250 × 5 = 1250 gm cal/cm^2/year, neglect of which might be equivalent to an overestimation of evaporation by about two cm/year. With the annual evaporation estimated as slightly over 100 cm, the error would be two per cent. This value of the error is very probably on the high side, because the inflow of water from the Mediterranean (Sea of Marmara) is likely to increase and not decrease the heat content of the Black Sea. The above considerations indicate that it is justified to neglect the term representing horizontal advection of energy.

There is one factor which reduces the computed difference in evaporation between the two water bodies. For the 40-45° zone of the North Atlantic, Bowen's ration is 0.076 [JACOBS, 1942] while for the Black Sea the same ratio is about twice as great (see Table 2) in consequence of the great temperature contrast in winter between the sea surface and the air coming from the cold continent. However, this difference is too small to eliminate the difference in evaporation as computed.

The section entitled Annual energy balance and evaporation below contains a summary of the energy balance computations while the following section attempts to give some details of the seasonal variation of evaporation. The last section discusses the results of the present calculations and their relations to the hydrologic balance of the sea.

Data and method--Values of air temperature, cloudiness, and pressure over the sea have been taken from Landsberg's bimonthly maps. On comparing his values with data of coastal stations [BIEL, 1944] we have found it necessary to increase slightly Landsberg's air temperature values for the winter months, as they appeared to be too low. With respect to the vapor pressure in the air, it was assumed that over the sea it is 1.5-2.5 mb higher than over the nearest coastal or land stations.

Values of sea-surface temperatures have been extracted from a file of averages (in the archives of the Meteorological Service, Israel) compiled from observations by British ships. Lastly, the salinity at the sea surface was taken as 17 $^0/oo$ [SVERDRUP and Others, 1946, pp. 650-651]. The empirical equation [loc. cit., p. 115]

$$e_w = e_d (1 - 0.000537 S) \quad \ldots\ldots (1)$$

where e_d is the vapor pressure of distilled water and e_w the vapor pressure of sea water, at the same temperature as the distilled water, and of salinity S (S being expressed in parts pro mille), indicates that a salinity of 17 $^0/oo$ causes a reduction of the vapor pressure by one per cent. Throughout this paper, the vapor pressure of the sea surface has been taken as one per cent less than the vapor pressure of distilled water at the same temperature.

For computing insolation, we have followed the summary by KLEIN [1948]

$$Q_s = Q_o (1 - 0.071 c) \quad \ldots\ldots (2)$$

This was used to compute the depletion of insolation by c-tenths of cloud, Q_o being the insolation from a cloudless sky.

Table 2--Meteorological data and energy balance of the Black Sea

Item	A 45°N 31°30′E	B 42°30′N 30°E	C 43°N 35°E	D 42°30′N 40°E
(a) Meteorological data, annual averages				
Sea-surface temperature, T_w, °C	13.9	14.6	14.5	14.8
Air temperature, T_a, °C	12.9	14.1	13.8	14.1
Vapor pressure of the sea surface, e_w, mb	15.8	16.4	16.3	16.7
Vapor pressure of air (estimated), e_a, mb	12.6	13.6	13.4	14.2
Pressure, p, mb	1,017	1,017	1,017	1,017
Cloud amount, c, tenths	5.1	5.3	5.1	5.3
(b) Energy balance, annual (= summation of monthly amounts)				
Insolation, Q_s[a]	137,700	137,000	140,200	133,600
Insolation reflected from sea surface, r_sQ_s ($r_s = 0.06$)[a]	8,800	8,800	9,000	8,600
Atmospheric radiation (long waves), Q_a[a]	241,000	247,400	245,500	248,200
Atmospheric radiation reflected from the sea surface, $r_\ell Q_a$ ($r_\ell = 0.03$)[a]	7,200	7,400	7,400	7,500
Long-wave radiation from the sea surface, $\epsilon\sigma T_w^4$ ($\epsilon = 0.97$)[a]	287,700	290,000	290,300	291,300
Net radiative balance at sea surface, $Q_r = Q_s + Q_a - (r_sQ_s + r_\ell Q_a + \epsilon\sigma T_w^4)$[a]	75,000	78,200	79,000	74,400
Bowen's ratio, $64.10^{-5}\, p\, \frac{T_w - T_a}{e_w - e_a} = R$	0.20	0.11	0.16	0.18
Sensible heat transferred from sea to air, Q_c[a]	12,500	7,700	10,900	11,300
Latent heat transferred from sea to air, Q_e[a]	62,500	70,500	68,100	63,100
Heat of vaporization, L, gm cal/gm	590	589	589	589
Evaporation, $E = Q_e/\rho L$, cm	104	118	114	106

[a] Gm cal/cm^2/year.

Note: Salinity is taken as 17 °/oo corresponding, at a sea surface temperature $T_w = 14.4$°C, to a density $\rho = 1.015$.

A fraction of the insolation is being lost by reflection from the sea surface. LAUSCHER [1952] has considered recently the theory of reflection of the direct and diffuse solar radiation from a water surface. His results [LAUSCHER, 1952, p. 183, fig. 7] indicate that for the latitudes of the Black Sea, the reflectivity for the daily amount of direct solar radiation is about 0.04 for June and July, the curve being rather flat about this minimum value, whereas it rises to a sharp peak of 0.15 for December. As to the diffuse solar radiation, Lauscher shows that for a sky of uniform brightness, theory predicts a reflectivity of 0.066, but if the brightness increases from zenith to horizon, reflectivity increases to a theoretical maximum of 0.177. The values of reflectivity measured by POWELL and CLARKE [1936] and by NEIBURGER [1948] fall between these limits but rather nearer to the lower value.

An application of the above results is difficult inasmuch as it is uncertain what fraction of the computed insolation be considered as direct solar radiation. KLEIN [1948, p. 124] cites an empirical formula relevant to the question. We have tested the formula on some observational data published of late and found that the agreement is not satisfactory. In view of these difficulties, it was decided to adopt the following values of reflectivity for the daily amounts of total insolation: March through September, 0.06; February and November, 0.08; and January and December, 0.10. The value adopted for January and December might seem low in comparison with Lauscher's results for the reflection of direct solar radiation. For the winter months, however, when the sky coverage by clouds is extensive and the altitudes of the Sun are relatively low, the share of the diffuse solar radiation in the total insolation may be expected to be the greater. As the reflectivity of the diffuse solar radiation appears to be mostly between 0.066 and 0.10, we have adopted for the reflectivity of the daily total insolation the value of 0.10 which is believed to be a reasonable weighted mean value.

In computing atmospheric radiation Q_a, BOLZ and FALCKENBERG's [1949] curve for average atmospheric turbidity was used. The values which refer to a cloudless sky, were corrected for cloudiness in accordance with BOLZ's [1949] results. Following the findings of the Lake Hefner Studies [ANDERSON, 1952, pp. 96-98], the reflectivity r_ℓ of the sea surface for long-wave radiation was taken as 0.03, a figure which is in fair agreement with theory [LAUSCHER, 1952, p. 184].

The long-wave radiation from the sea surface to the atmosphere was calculated from $\epsilon\sigma T_w^4$, where T_w is the sea surface temperature, now in °K, σ the Stefan-Boltzmann constant ($\sigma = 8.26 \times 10^{-11}$ gm cal/cm^2 min deg^4), and ϵ the emissivity of the sea surface: $\epsilon = 1 - r_\ell$.

In summary, the effective back radiation Q_b from the sea surface to a cloudy sky is obtained from

$$Q_b = 0.97\,\sigma T_w^4 - Q_a + 0.03\,Q_a = 0.97\,(\sigma T_w^4 - Q_a) \quad \ldots\ldots\ldots\ldots (3)$$

In agreement with results of the estimate for the possible magnitude of horizontal energy advection, this term is neglected throughout.

Annual energy balance and evaporation--The detailed computations have been carried out for four distinct points marked A, B, C, and D in Figure 1. In the figure, the 'numerators' and the 'denominators' of the 'fractions' state the amount of sensible and latent heats respectively, in gm cal/cm^2/day, transferred from the sea to the atmosphere. Their ratio gives the annual value of Bowen's ratio. Figures in circles adjacent to the 'fractions' represent the annual amount of evaporation in centimeters.

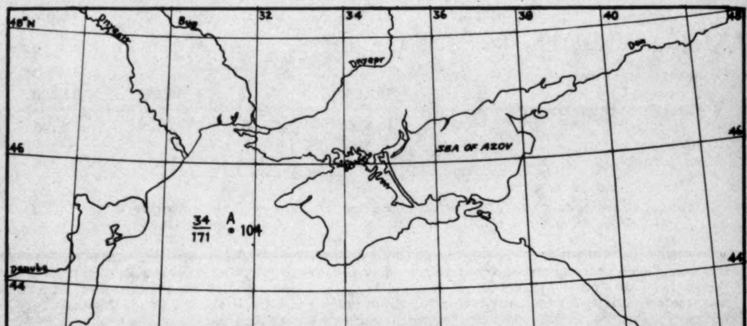

Fig. 1--The Black Sea - energy interchange between sea and atmosphere; numerators of 'fractions,' sensible heat transferred, in gm cal/cm^2/day; denominators, latent heat transferred, in similar units; figures to the right of circles are the annual amount of evaporation, in centimeters; scale, 1:9,000,000

Table 2 is a summary of the data and of the energy balance for each of the four points. The terms of the radiative balance have been computed for monthly periods, interpolating where necessary between the values read off Landsberg's bimonthly isopleths to obtain the meteorological data needed for the monthly computations. However, the table only states the annual sums of the radiative balance.

In assessing the limits of error for the computed values of evaporation, it may be pointed out that for the points on or near 43°N (B, C, and D), the computed value of insolation is in close agreement with Kimball's figures [SVERDRUP and Others, 1946, p. 103] for the amounts of insolation reaching the sea surface over sections of the 42° parallel of latitude of the North Atlantic and North Pacific, if due allowance is made for differences in cloudiness in accordance with (2). It is, however, difficult to assess the error of the various radiation terms as it is not known how well the empirical formulas represent conditions in the Black Sea region.

A further source of error is the Bowen ratio, both for theoretical and practical reasons. On the theoretical side, its derivation involves assumptions which are not certain to be valid under all conditions of atmospheric stability. On the practical side, the meteorological data serving as basis for the calculations are, excepting the sea-surface temperatures, extrapolations.

Table 2 indicates that the average annual evaporation from the Black Sea is 110 cm, approximately. On the more detailed side, the results bear the principal characteristics of the energy interchange between the oceans and the atmosphere. Evaporation decreases from south to north and from west to east. The latter is a combined effect of the increasing values of humidity and cloudiness from west to east. Although the former values are based on estimates, the high values of humidity at Batum [BIEL, 1944, p. 109] appear to lend support to our assumptions. In agreement herewith is the fact that offshore winds prevail in the west, with the effect of a lowering of humidity and of cloud amount, whereas the mountain barrier of the Caucasus and the prevailing circulation increase the share of onshore winds in the eastern part of the sea.

About the annual variation of evaporation--Despite the absence of information on the annual variation of temperature with depth of the sea, it is still possible, as is shown elsewhere [NEUMANN, 1953], to calculate the evaporation for two half-yearly or approximately half-yearly periods, if an assumption is made in respect of the average dates when the sea column in question reaches its lowest temperature (average of column) T_n late in winter and its highest temperature T_x late in summer. The difference of heat contents of a column of one cm^2 cross-section at the dates of occurrence of T_x and T_n gives the so-called annual heat budget Q_H in gm cal/cm^2.

If we denote by

Q	the amount of energy available for transfer from the sea surface to the atmosphere and/or to the sea, in gm cal/cm^2
R	the Bowen ratio
L	the latent heat of vaporization, in gm cal/gm of water at the average temperature of the sea surface
ρ	the density of evaporating sea water, in gm/cm^3
E	the evaporation, in cm

and if superscript ′ refers to values of the variable appropriate for the period between the dates of T_n and T_x to be called Period 1, supercript ″ refers to the period between T_x and T_n to be called Period 2, while without superscripts, the symbols relate to a full annual cycle, then it can be shown [NEUMANN, 1953] that to a high degree of approximation the annual heat budget Q_H is

$$Q_H = \frac{(1 + R'')(R - R')Q' - (1 + R')(R'' - R)Q''}{(1 + R)(R'' - R')} \quad \ldots\ldots\ldots\ldots (4)$$

It also follows from the energy equation for average conditions that evaporation in Periods 1 and 2, respectively, is

$$E' = \frac{Q' - Q_H}{\rho' L' (1 + R')} \qquad E'' = \frac{Q'' + Q_H}{\rho'' L'' (1 + R'')} \quad \ldots\ldots\ldots (5)$$

and

$$E = E' + E'' \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

If then one computes Q_H from (4), one can also compute, to an approximation, the evaporation in Period 1 (spring-summer) and Period 2 (autumn-winter), respectively.

We have applied (4) and (5) to the conditions at points A, B, C, and D (Fig. 1) and arrived at the results tabulated in Table 3. It is assumed for the purposes of the present calculations that the date of T_n is March 16 and that of T_x August 31. A further assumption of Table 3 is that advective terms of the semestrial energy balances are small. Energy interchanges between the sea and its bed are only important in the shallower sections of the sea and even there they are relatively small. BOWDEN's [1948] work in connection with the Irish Sea indicates that the effect of sea bed is to increase the apparent thermal capacity of the sea by that of a water layer one meter thick.

Table 3--Annual heat budgets and evaporation in the spring-summer and autumn-winter half-yearly periods respectively for selected areas of the Black Sea[a]

Period	Item	A	B	C	D
Mar. 16 - Aug. 31	Q', gm cal/cm^2	64,800	62,300	67,100	60,700
Sep. 1 - Mar. 15	Q'', gm cal/cm^2	10,200	15,900	11,900	13,700
Mar. 16 - Aug. 31	R'	-0.151	-0.090	-0.264	-0.243
Sep. 1 - Mar. 15	R''	0.455	0.250	0.365	0.372
Annual	R	0.204	0.111	0.163	0.183
Annual	Q_H, gm cal/cm^2	42,900	35,300	51,100	46,100
Mar. 16 - Aug. 31	L', gm cal/gm	588	587	587	587
Sep. 1 - Mar. 15	L'', gm cal/gm	591	590	590	590
Annual	L, gm cal/gm	590	589	589	589
Mar. 16 - Aug. 31	E', cm	43	50	37	32
Sep. 1 - Mar. 15	E'', cm	61	68	77	74
Annual	E, cm	104	118	114	106

[a] Density ρ of the surface waters of the sea has been assumed 1.015 throughout. The error due to disregard of an annual variation is negligible.

Although the results in Table 3 are subject to an error of several per cent, the differences between the computed values of evaporation for the two semesters are sufficiently great to conclude that like in the case of the oceans, autumn and winter amounts of evaporation from the Black Sea considerably exceed the amounts for the spring-summer semester.

Relation of the present results to hydrology of the sea--The results of the present note suggest the need for a revision of the hydrologic balance proposed by Sverdrup. To account for an evaporation of 110 cm, the 'gains' side of the balance sheet would have to be increased by 26 cm. With a sea area of 420,000 km^2, the additionally required inflow should amount to about 1.1×10^{11} m^3/year or 3450 m^3/sec. The sources for this inflow may be a combination of (1) a greater inflow from the Mediterranean and (2) a larger value of precipitation or runoff or both.

It is unlikely that inflow from the Mediterranean is greater or at least sensibly greater than that deduced from Merz's observations which have been accepted by both Sverdrup and Wüst, as mentioned before. A larger inflow from the Mediterranean as well as a larger evaporation, as suggested by the present paper, would make it difficult to explain the maintained low salinity of the sea.

It has indeed been suggested by ULLYOTT and ILGAZ [1946] that there is practically no inflow at all from the Mediterranean (Sea of Marmara), or rather that the bottom current of the Bosporus which is directed from the Sea of Marmara is returned by a topographical barrier at the entrance to the Black Sea. They estimate the average outflow through the Bosporus to amount to some 33,000 m^3/sec. The outflow suggested by the above two authors would require for its maintenance an annual amount of precipitation and runoff of approximately 245 cm. An additional 100 cm or so would be required to make up for evaporation, bringing the total loss to some 350 cm/year. Of this, about 58 cm is supplied by precipitation over the sea [see water balance by SVERDRUP and Others, 1946, p. 650] leaving some 290 cm to come from runoff to the sea. Since the area of the catchment (land) of the sea is some 5.75 times larger than the surface area of the sea (see below), a runoff of 290 cm for the sea would mean a runoff of about 50 cm from the catchment. Now, according to the authors' estimate, the average annual rainfall over the catchment amounts to 55.3 cm. The suggestions of Ullyott and Ilgaz would thus necessitate an extraordinarily high percentage of the rainfall of the catchment to reach the sea as runoff.

In view of the above considerations, it has appeared worthwhile to undertake a re-evaluation of the amount of runoff from the catchment of the sea as well as that of precipitation over the sea itself. It might be pointed out in this connection that only recently it was found necessary to revise previous estimates of these terms for the Mediterranean [WÜST, 1952].

The hydrographic data available to the authors for the catchment area of the Black Sea cover 92 pct of the catchment. Data for the total catchment of the Danube and partial catchments of the Dnyepr, Don, Kuban, and Dnyestr were extracted from an English translation of a paper by LVOVICH [1945], data for partial catchments of five Turkish rivers were taken from KARATEKIN [1953]; furthermore, an evaluation of the runoff from the Russian part of the catchment of the Black Sea not covered by the data from Lvovich was made on the basis of the runoff map by Zaĭkov, published in a reduced scale (1:15×10^6) by LEĬVIKOV [1949]; as stated by the latter, Zaikov's map is the result of research of 20 years or more, and based on hydrological data only. The data thus received are summarized in Table 4.

Table 4--Estimation of runoff from Black Sea catchment

River or part of catchment	Area	Runoff			Authority
	$km^2 \times 10^{-3}$	cm/yr	$m^3/yr \times 10^{-9}$	m^3/sec	
Danube	817.0	24.6	201.0	6,373	Lvovich
Dnyepr[a]	459.1	11.4	52.3	1,660	Lvovich
Don[a]	223.9	9.7	21.7	689	Lvovich
Kuban[c]	45.4	26.8	12.2	386	Lvovich
Dnyestr[c]	44.0	15.5	6.8	216	Lvovich
Five Turkish rivers[a]	116.6	10.0	11.7	371	Karatekin
Rest of Russian part of catchment[c]	522.5	15.5	81.0	2,569	Zaĭkov
Total	2,228.5	...	....	12,264	....
Total catchment of Black Sea[b]	2,412	...	....	13,550	Hydrological balance of present paper (see below)
Percentage of catchment (runoff)	92	...	....	91	....

[a] The catchment area of the rivers Dnyepr and Don as given by Lvovich form 91 and 52 pct, respectively, of the total catchment of these rivers; those of the Turkish rivers as given by Karatekin form 66 pct of the total catchment of the same rivers.

[b] The area not assessed in the table consists of the southern Rumanian and Bulgarian part of the catchment, and that of Turkey except for the five river catchments given by Karatekin.

[c] Area determinations other than those given by Lvovich and Karatekin were made on the base of the International Map 1:10^6.

Table 4 shows that there is a close agreement between the percentage of the catchment area of the Black Sea covered by data available to the authors from the total catchment, and of the runoff of this area from the total runoff as received from energy balancy considerations, hydrologic data of the flow through the Bosporus and the estimation of the precipitation over the Black Sea only. It may be pointed out that the runoff based on the data of Lvovich and Karatekin alone form 93 pct of the runoff as given by SVERDRUP and Others [1946], whereas the area accounted for by these data (1,706,000 km^2) forms only 71 pct of the total catchment (2,412,000 km^2) of the sea.

The authors have also made an attempt to estimate the amount of precipitation falling over the sea. Their result was close to the value adopted by Sverdrup, which is 58 cm/year, or 7600 m^3/sec, or 2.4×10^{11} m^3/year. Because of the small difference between the two estimates and the uncertainties involved in estimates of precipitation over the sea, the authors prefer to accept Sverdrup's figure.

In view of the facts that (1) the precipitation amount over the sea estimated by them is close to the value quoted by Sverdrup, and (2) the figures for runoff and precipitation support the evaporation amount computed from the energy balance if Merz's figures for the in- and outflow through the Bosporus are adopted, the hydrologic balance given in Table 5 is suggested for the sea.

Table 5--Hydrologic balance of the Black Sea

Gains	Amount	Losses	Amount
	m^3/sec		m^3/sec
Inflow through Bosporus	6,100	Outflow through Bosporus	12,600
Precipitation	7,600	Evaporation	14,650
Runoff	13,550		
	27,250		27,250

If our considerations are correct, then the quantity E - P (evaporation minus precipitation and runoff) for the Black Sea remains -2.1×10^{11} m^3/year (-50 cm/year) which is Sverdrup's estimate.

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SEEPAGE OF ARTESIAN AND SURFACE WATER INTO DRAIN TUBES IN STRATIFIED SOIL

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Abstract--The problem of the simultaneous upward seepage of water from an artesian basin, and downward seepage of water from a ponded surface source into drain tubes, is analyzed for a soil consisting of two horizontally stratified layers, each of different, but uniform permeability, overlying the artesian gravel. Theoretical formulas for the hydraulic head, the drain flow, and the surface inflow distribution are obtained for two cases: (1) the drains are in the upper layer; and (2) the drains are in the lower layer. Flow nets are presented and compared with some obtained by other investigators in sand tank models. The agreement is satisfactory.

This paper can be considered as part IV of a series [KIRKHAM, 1945, and papers there cited] dealing with the seepage of water from an artesian basin into drain tubes. In the former papers a soil of uniform permeability overlying artesian gravel was considered. In the present paper the problem is considered when the soil overburden consists of two horizontal layers each of different but of uniform permeability. There are two cases: (1) the drains are in the upper stratum (Fig. 1A); and (2) the drains are in the lower (Fig. 1B). In both cases the drains are taken to be equally spaced; therefore, as in the earlier problems, only a typical section, as the soil between two vertical planes passing through the axes of adjacent tubes, need be considered.

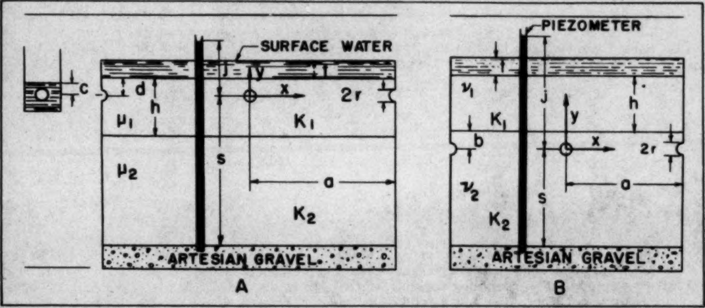

Fig. 1--Representation of typical vertical section through drain tubes in stratified soil with ponded surface water and artesian pressure; (A) drains in the upper stratum, (B) drains in the lower stratum; the symbols μ_1 and μ_2 and ν_1 and ν_2 denote the hydraulic head for points (x, y) in the upper and lower strata of hydraulic conductivities K_1 and K_2; the head c in the outflow facility, as a ditch or sump, is indicated at left only; standpipe head is j; heads are referred to level of drain tube centers

Analysis, Figure 1A

The drains of depth d, radius r, and spacing a are located in the upper soil stratum of hydraulic conductivity K_1 and of thickness h. The hydraulic conductivity of the lower stratum is K_2 and its thickness s - (h - d), s being the distance from the level of drain centers to the artesian gravel. The term hydraulic conductivity is used for K_1 and K_2, rather than permeability, in accordance with a recommendation from the Soil Science Society of America [see RICHARDS, 1952]. Water of thickness t stands on the soil surface, and stands to a level $j + s$ in a piezometer penetrating into the gravel. An x,y-system of coordinates is chosen with origin at the center of a drain tube; y is taken vertically upward, x horizontally to the right.

The reference level for hydraulic head is taken at the level of the drain centers. The symbols μ_1 and μ_2 denote respectively the hydraulic head (potential) at points in the upper and lower strata. Therefore, μ_1 or μ_2 is the height, referred to the level of the drain centers, at which water will stand in a piezometer whose end is at any point x,y in question. The drains are initially assumed to be completely pervious to flow. Later, correction terms will be given for taking account of flow, as into farm tile drains, where the water enters the drains only at joints between the tile units. The drain tubes are assumed running full with either constant back pressure or suction c, c being a head referred to the level of the drain centers. The head c can be positive if the outlets are submerged, and negative (suction) if the outlets are at a lower level than the principal array of drains.

Readers not wishing to follow mathematical details may at this point skip to the section Results and Discussion.

Boundary conditions--The functions μ_1 and μ_2 must satisfy Laplace's equation and the following boundary conditions

$$y = -(h - d) \qquad \mu_1 = \mu_2 \; \ldots\ldots\ldots\ldots \text{Condition I}$$

$$y = -(h - d) \qquad K_1 \partial\mu_1/\partial y = K_2 \partial\mu_2/\partial y \; \ldots\ldots \text{Condition II}$$

$$y = d \qquad \mu_1 = t + d \; \ldots\ldots\ldots \text{Condition III}$$

$$y = r, x = 0 \qquad \mu_1 = c \; \ldots\ldots\ldots\ldots \text{Condition IV}$$

$$y = -s \qquad \mu_2 = j \; \ldots\ldots\ldots\ldots \text{Condition V}$$

In the following it is assumed that the reader has at hand a copy of KIRKHAM [1951]. At least two printed pages are saved by not recopying here certain long expressions given there which are needed here. The symbols here will be, as much as practical, the same as there. The next four equations are copied from the earlier papers.

$$X = \cos 2\pi x/a \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

$$v = (1 - K_2/K_1)/(1 + K_2/K_1) \; \ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

$$K_2/K_1 = (1 - v)/(1 + v) \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

n = an integer to be chosen such that

$$2nh - d > a \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4)}$$

Some other expressions will be needed from the earlier work. They will be referred to in a rather unconventional, but space-saving manner. Derived and auxiliary equations, which follow, are not presented in the order they naturally occur, but in the order that a mathematical reader can verify them readily. Also, for the aid of the reader, when a series of equations are referred to, they are listed in the order of their indicated use--not in numerical order.

Potentials ϕ_1' and ϕ_2' which satisfy Conditions I, II, and III are given by KIRKHAM [1951, Eq. (15bc)] where primes are added to denote that the value of the constant f_o there must be changed to f_o'. The constant f_o may be changed to f_o' since ϕ_1' and ϕ_2' satisfy Conditions I, II, and III for any constant value of f_o.

Thus

$$\phi_1' = f_o' \left\{ \text{material in braces } \{\} \text{ of KIRKHAM [1951, Eq. (15b)]} \right\}$$
$$- (-1)^n v^n (4\pi d/a)\, f_o' + t + d \; \ldots\ldots\ldots\ldots\ldots\ldots \text{(5)}$$

$$\phi_2' = (1 + v)\, f_0' \Big(\text{material in large parentheses ( ) of KIRKHAM [1951, Eq. (15c)]}\Big)$$
$$- (-1)^n v^n (4\pi d/a)\, f_0' + t + d \quad \ldots\ldots (6)$$

$$[\phi_1']_{y=-(h-d)} = [\phi_2']_{y=-(h-d)} \quad \ldots\ldots (7)$$

$$K_1\, [\partial\phi_1'/\partial y]_{y=-(h-d)} = K_2\, [\partial\phi_2'/\partial y]_{y=-(h-d)} \quad \ldots\ldots (8)$$

$$[\phi_1']_{y=d} = t + d \quad \ldots\ldots (9)$$

Regarding Condition V the following important observation is made. If $s > a/2$, or for greater accuracy of results, if

$$s > a \quad \ldots\ldots (10)$$

then each of the log terms in ϕ_2' assumes a value which becomes independent of x [see MUSKAT, 1937, Fig. 201]. Therefore, if one takes $s > a$ or $> a/2$ (which covers cases in practice) and lets A_1, A_2, A_3, and A_4 be constants to be suitably chosen, then, as will be shown, potentials μ_1 and μ_2 which satisfy the boundary conditions are

$$\mu_1 = \phi_1' + A_1 y + A_2 \quad \ldots\ldots (11)$$

$$\mu_2 = \phi_2' + A_3 y + A_4 \quad \ldots\ldots (12)$$

From (11), (12), Conditions I, II, III, and (7), (8), (9)

$$A_1 = (K_2/K_1)\, A_3 \quad \ldots\ldots (13)$$

$$A_2 = -\, d\, (K_2/K_1)\, A_3 \quad \ldots\ldots (14)$$

$$A_4 = (h - d - hK_2/K_1)\, A_3 \quad \ldots\ldots (15)$$

To evaluate A_3 and f_0', auxiliary constants B, C, D, E, and F are next defined. In the expression for E below, any value of x can be chosen, since E is independent of x. The value $x = 0$ ($X = 1$) is chosen in E in order to keep the construction of E parallel to that of C. In C the value $x = 0$ stems from Condition IV. The quantities B, C, D, E, and F are, then

$$B = \Big\{\text{Material in braces \{ \} of (15b) of KIRKHAM [1951] with } y = r \text{ and } X = 1\Big\} \quad \ldots (16)$$

$$C = (-1)^n v^n (4\pi d/a) = (-v)^n (4\pi d/a) \quad \ldots\ldots (17)$$

$$D = -\,(B - C) \quad \ldots\ldots (18)$$

$$E = (1 + v) \Big(\text{material in large parentheses ( ) of KIRKHAM}$$
$$\text{[1951, Eq. (15c) with } y = -s \text{ and } X = 1]\Big) \quad \ldots\ldots (19)$$

$$F = -\,(E - C) \quad \ldots\ldots (20)$$

From (5), (6), and (16) to (20)

$$[\phi_1']_{y=r,\ x=0} = f_0'\,(-D) + t + d \quad \ldots\ldots (21)$$

$$[\phi_2']_{y=-s,\ (x=a/4)} = f_0'\,(-F) + t + d \quad \ldots\ldots (22)$$

Let further auxiliary quantities be

$$G = (d - r)\, K_2/K_1 \quad \ldots\ldots (23)$$

$$I = s - (h - d) + hK_2/K_1 \quad \ldots\ldots (24)$$

Then from Condition IV, (11), (5), (16), (17), (18), (13), (14), (23); and from Condition V, (12), (6), (19), (17), (20), (15), (24); one finds two equations in A_3 and f_0' which yield

$$A_3 = -\Big\{[j - (t + d)]\, D + (t + d - c)\, F\Big\}/(DI - FG) \quad \ldots\ldots (25)$$

$$f_o' = \left\{[j - (t + d)]\, G + (t + d - c)\, I\right\}/(DI - FG) \quad \ldots\ldots\ldots\ldots\ldots (26)$$

Equations (13), (14), (15), (25), and (26), together with the auxiliary quantities D, F, G, and I, constitute the solutions of the A's and f_o' for (11) and (12).

The quantities D and F, as given by (18) and (20), are not in very useful form. A useful expression for (18) is seen to be

$$D = \text{RHS of KIRKHAM } [1951,\ \text{Eq. } (17)] \quad \ldots\ldots\ldots\ldots\ldots (27)$$

(RHS means right-hand side.) A useful expression for (20) can be obtained as follows. One expands first the RHS of (19) (thereby remembering that $\cosh 2\pi(-s)/a = \cosh 2\pi s/a$, etc.; and taking, in view of (10), $\cosh 2\pi s/a + 1 = \cosh 2\pi s/a = (1/2)\, e^{2\pi s/a}$, etc.) and obtains

$$E = (1 + v)\,(-\,4\pi d/a)\,[1 - v + v^2 - v^3 + \ldots - (-1)^n v^{n-1}] \quad \ldots\ldots\ldots\ldots\ldots (28)$$

One next notes that the square bracket in (28) is a geometrical progression; successive terms are in the ratio $(-v)$. Therefore, from Eq. (26) of DWIGHT [1947]

$$1 - v + v^2 - v^3 + \ldots - (-1)^n v^{n-1} = [1 - (-v)^n]/(1 + v) \quad \ldots\ldots\ldots\ldots\ldots (29)$$

and (28) becomes

$$E = -\,(4\pi d/a)\,[1 - (-v)^n] \quad \ldots\ldots\ldots\ldots\ldots (30)$$

From (20), (30), and (17)

$$F = 4\pi d/a \quad \ldots\ldots\ldots\ldots\ldots (31)$$

a surprisingly simple result.

Computation of the drain flow Q--Let Q denote the quantity of seepage water entering unit length of drain tube per unit time. Then, from Darcy's law, considered at points (x_1, y_1) near the drain tube surface where $r_1^2 = x_1^2 + y_1^2$, and where $\partial\mu_1/\partial r_1$ is the hydraulic gradient and dS is an element of the surface area, one has

$$Q = K_1 \int_S [\partial\mu_1/\partial r_1]_{r_1=r}\, dS \quad \ldots\ldots\ldots\ldots\ldots (32)$$

Now, from (11), (5), and (1), and since the drain radius r will be small compared to d, a, and s, one can write down for points near the drain surface

$$\mu_1 = f_o' \log_e (\cosh 2\pi y/a - \cos 2\pi x/a) + \text{nearly constant terms} + A_1 y + \text{constant} \ldots\ \ldots\ldots (33)$$

Therefore, ignoring for the moment the term A_1y, one has, following the argument below KIRKHAM [1945, Eq. (37)]

$$Q = 4\pi K_1 f_o'$$

The term A_1y in (33) need not be ignored to obtain the last equation. The reason is that for each contribution $[\partial(A_1y)/\partial r_1]\, dS$, to the integral in (32), for a point (x, y) on the upper half of the tube, there corresponds a term $-[\partial(A_1y)/\partial r_1]\, dS$ at a point (x, -y) on the lower half. The total contribution from A_1y to the integral is thus zero. The cancellation of the flow components arising from A_1y does not mean that the effect of linear flow is not taken account of in Q. The effect of linear flow is embodied in the coefficient f_o'.

If (26) is used with the last equation, Q becomes

$$Q = 4\pi K_1 \left\{[j - (t + d)]\, G + (t + d - c)\, I\right\}/(DI - FG) \quad \ldots\ldots\ldots\ldots\ldots (34)$$

Intake rate Q′ per unit area at the soil surface; flow nets--Let Q′ denote the quantity of water entering unit area of the soil surface in a unit time. Then, from (11) and Darcy's law

$$Q' = K_1\, [\partial\mu_1/\partial y]_{y=d} \quad \ldots\ldots\ldots\ldots\ldots (35)$$

Now let

$$M = \text{RHS of KIRKHAM [1951, Eq. (21)]} \qquad (36)$$

Then from (35), (11), (5), (1), and (36)

$$Q' = K_1 (4\pi f_o' M/a + A_1) \qquad (37)$$

Equipotentials and streamlines for any particular values of the geometry and of K_1/K_2 for Figure 1A and 1B may be obtained, as was done in earlier work [KIRKHAM, 1951], by writing down complex potentials corresponding to (11) and (12) and then using Kennelly's tables there referred to. These potentials are space consuming and need not be written down here. In using these new complex potentials with Kennelly's tables, it is necessary to change Kennelly's angles in degrees to angles in radians. This was not necessary in former work.

Analysis, Figure 1B

The geometry and symbols for Figure 1B are the same as in Figure 1A except that ν_1 and ν_2 are the hydraulic head functions and b is the distance of the drain tube center below the division plain of the two soil strata, the depth of the drains now becoming h + b. As before, the reference level for hydraulic head is taken at the level of centers of drain tubes. The analysis, although similar to that for Figure 1A, is different enough to warrant its presentation, in some detail.

Boundary conditions are

$y = b \qquad \nu_1 = \nu_2$ .... Condition I'

$y = b \qquad K_1 \partial \nu_1/\partial y = K_2 \partial \nu_2/\partial y$ ..... Condition II'

$y = h + b \qquad \nu_1 = b + h + t$ ...... Condition III'

$y = r, x = 0 \qquad \nu_2 = c$ .... Condition IV'

$y = -s \qquad \nu_2 = j$ .... Condition V'

Let s_o' be a constant to be evaluated, and let

$$k = \text{an integer such that } [(2k + 1) h + b] > a \qquad (38)$$

$$\theta_1' = (1 - v) s_o' \Big(\text{material in large parentheses } (\,) \text{ of KIRKHAM [1951, Eq. (40b)]} \Big) + b + h + t \qquad (39)$$

$$\theta_2' = s_o' \Big\{ \text{material in braces } \{\} \text{ of KIRKHAM [1951, Eq. (40c)]} \Big\} + b + h + t \qquad (40)$$

Then, independently of s_o'

$$[\theta_1']_{y=b} = [\theta_2']_{y=b} \qquad (41)$$

$$K_1 [\partial \theta_1'/\partial y]_{y=b} = K_2 [\partial \theta_2'/\partial y]_{y=b} \qquad (42)$$

$$[\theta_1']_{y=b} = b + h + t \qquad (43)$$

With α_1, α_2, α_3, and α_4 constants to be determined, let

$$\nu_1 = \theta_1' + \alpha_1 y + \alpha_2 \qquad (44)$$

$$\nu_2 = \theta_2' + \alpha_3 y + \alpha_4 \qquad (45)$$

Then from (44), (45); Conditions I', II', III'; and (41), (42), (43)

$$\alpha_1 = (K_2/K_1) \alpha_3 \qquad (46)$$

$$\alpha_2 = -(K_2/K_1)(h + b)\,\alpha_3 \tag{47}$$

$$\alpha_4 = -(b + hK_2/K_1)\,\alpha_3 \tag{48}$$

Let

$$L = -\left\{\text{material in braces } \{\,\} \text{ of KIRKHAM } [1951, \text{Eq. (40c) with } y = r \text{ and } X = 1]\right\} \tag{49}$$

$$N = -\left\{\text{material in braces } \{\,\} \text{ of KIRKHAM } [1951, \text{Eq. (40c) with } y = -s \text{ and } X = 1]\right\} \tag{50}$$

$$P = b - r + hK_2/K_1 \tag{51}$$

$$R = b + s + hK_2/K_1 \tag{52}$$

$$H = b + h + t \tag{53}$$

Then from (45), (40), Condition IV′, (49), (53), (48), (51); and from (45), (40), Condition V′, (50), (53), (48), (52); one finds as for (25) and (26) two equations in α_3 and s_o' which yield

$$\alpha_3 = -[(j - H)\,L + (H - c)\,N]/(LR - NP) \tag{54}$$

$$s_o' = [(j - H)\,P + (H - c)\,R]/(LR - NP) \tag{55}$$

The quantities L and N, (49) and (50), can be simplified. L will first be simplified. The corresponding simplified form of N can then be written down by changing r to (-s), and L to N, in the expression for L, as is evident by comparing (49) and (50).

Let

$$\begin{aligned} S = {} & \log_e[\cosh 2\pi(2h + 2b - r)/a - 1] - v \log_e[\cosh 2\pi(4h + 2b - r)/a - 1] \\ & + v^2 \log_e[\cosh 2\pi(6h + 2b - r)/a - 1] - \ldots - (-1)^k v^{k-1} \log_e[\cosh 2\pi(kh + 2b - r)/a - 1] - \ldots \end{aligned} \tag{56}$$

Then, from (49) and (56) (and remembering cosh (-A) = cosh A)

$$\begin{aligned} L = {} & -\left\{\log_e(\cosh 2\pi r/a - 1) - v \log_e[\cosh 2\pi(2b - r)/a - 1]\right\} + (1 - v^2)\,S \\ & + (-1)^k (1 - v)\, v^k [2\pi(2kh + h + b)/a - \log_e 2 - 2\pi(r - b - K_2h/K_1)/a] \end{aligned} \tag{57}$$

In (38) it was specified that $[(2k + 1)\,h + b]$ should be greater than a. Actually the larger the integer k, the more accurate the results. Therefore, let $k \to \infty$. Whence, since $|v| < 1$, $v^k \to 0$ and $kv^k \to 0$. Therefore, (the last term in (56) becoming linear in k), the last term in (56), and also in (57), becomes zero.

There is a difficulty with (56) as it stands. Its RHS converges slowly, because the values of succeeding logarithmic terms became larger, as more terms are taken. The convergence depends solely on the coefficients v, v^2, v^3, etc. To obtain a rapidly converging series, one proceeds as follows.

Let, using the notation exp x for e^x

$$\begin{aligned} T = {} & \log_e[\cosh 2\pi(2h + 2b - r)/a - 1]/(1/2)\exp 2\pi(2h + 2b - r)/a \\ & - v \log_e[\cosh 2\pi(4h + 2b - r)/a - 1]/(1/2)\exp 2\pi(4h + 2b - r)/a \\ & + v^2 \log_e[\cosh 2\pi(6h + 2b - r)/a - 1]/(1/2)\exp 2\pi(6h + 2b - r)/a - \ldots \end{aligned} \tag{58}$$

$$\begin{aligned} U = {} & \log_e(1/2)\exp 2\pi(2h + 2b - r)/a - v \log_e(1/2) \\ & \exp 2\pi(4h + 2b - r)/a + v^2 \log_e(1/2)\exp 2\pi(6h + 2b - r)/a - \ldots \end{aligned} \tag{59}$$

Then, one can write the identity

$$S = T + U \tag{60}$$

Now in (58) the RHS converges rapidly because the arguments of the logarithms approach unity (the logarithms themselves approaching zero) and the powers of v approach zero. The last statement is not true for (59) because the arguments of the logarithms approach infinity, and accordingly the overall situation for convergence does not appear improved. Improvement is achieved by summing the RHS of (59) analytically.

One writes (59) in the form

$$U = [2\pi(2b - r)/a - \log_e 2]\,(1 - v + v^2 - \ldots) + (4\pi h/a)\,(1 - 2v + 3v^2 - \ldots)$$

noting from (29) that $(1 - v + v^2 - \ldots) = 1/(1 + v)$; and from direct algebraic division of $(1 + v)^2$ into unity that $(1 - 2v + 3v^2 - \ldots) = 1/(1 + v)^2$; so that

$$U = [2\pi(2b - r)/a - \log_e 2]/(1 + v) + (4\pi h/a)/(1 + v)^2 \tag{61}$$

the result desired.

From (57), (60), and, remembering that the last terms in (56) and (57) become zero for large k, the resulting simplified form of L is

$$L = -\left\{\log_e (\cosh 2\pi r/a - 1) - v \log_e [\cosh 2\pi(2b - r)/a - 1]\right\} + (1 - v^2)\,(T + U) \tag{62}$$

or putting

$$\begin{aligned} L_1 = {} & v \log_e [\cosh 2\pi(2b - r)/a - 1] - \log_e (\cosh 2\pi r/a - 1) \\ & + (1 - v^2)\,T + (1 - v)\,[2\pi(2b - r)/a - \log_e 2] \end{aligned} \tag{63}$$

there results from (62), (61), (3), and (63)

$$L = L_1 + (4\pi h/a)\,K_2/K_1 \tag{64}$$

The quantity L_1 has been singled out from L, because, unlike the term $(4\pi h/a)\,K_2/K_1$, L_1 is finite for all K_2/K_1.

Remembering the statement preceding (56), the simplified form of N corresponding to L of (62) is

$$N = -\left\{\log_e (\cosh 2\pi s/a - 1) - v \log_e [\cosh 2\pi(2b + s)/a - 1]\right\} + (1 - v^2)\,(V + W)$$

where V and W are obtained by putting (-s) for r in the RHS of (58) and (61). Thus

$$\begin{aligned} V = {} & \log_e [\cosh 2\pi(2h + 2b + s)/a - 1]/(1/2) \exp 2\pi(2h + 2b + s)/a \\ & - v \log_e [\cosh 2\pi(4h + 2b + s)/a - 1]/(1/2) \exp 2\pi(4h + 2b + s)/a \\ & + v^2 \log_e [\cosh 2\pi(6h + 2b + s)/a - 1]/(1/2) \exp 2\pi(6h + 2b + s)/a - \ldots \end{aligned}$$

and

$$W = [2\pi(2b + s)/a - \log_e 2]/(1 + v) + (4\pi h/a)/(1 + v)^2$$

Because of (10) the expression for N can be further simplified. Since from (10), $\log_e (\cosh 2\pi s/a - 1) = 2\pi s/a - \log_e 2$, approximately, etc.; and since the argument of each log term in V is approximately unity, V being effectively zero, the better form of N is

$$\begin{aligned} N = {} & -\left\{2\pi s/a - \log_e 2 - 2\pi v\,(2b + s)/a + v \log_e 2\right\} \\ & + (1 - v^2)\left\{[2\pi(2b + s)/a - \log_e 2]/(1 + v) + (4\pi h/a)/(1 + v)^2\right\} \end{aligned}$$

which upon cancelling like terms and using (3) yields

$$N = 4\pi(b + hK_2/K_1)/a \tag{65}$$

a remarkably simple result in comparison with (50).

Formulas for the drain flow, surface inflow distribution and flow nets--The drain flow Q per unit length of drain tube is found, as below (33), to be

$$Q = 4\pi K_2 s_o'$$

or using (55)

$$Q = 4\pi K_2 [(j - H)\, P + (H - c)\, R]/(LR - NP) \quad \ldots\ldots\ldots\ldots\ldots (66)$$

The surface inflow rate Q′ per unit area per unit time is

$$Q' = K_1\, [\partial \nu_1/\partial y]_{y=d} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (67)$$

Letting

$$M' = (1 - v)\,(1/2)\,\Big(\text{material in large parentheses } (\;) \text{ of KIRKHAM [1951, Eq. (49)]}\Big) \ldots (68)$$

one has from (67), (44), (39), and (68)

$$Q' = K_1\, [(4\pi/a)\, S_o' M' + \alpha_1]$$

or using (55), (46), and (54), one has

$$Q' = K_1 \Big\{(4\pi/a)\, M' [(j - H)\, P + (H - c)\, R] - (K_2/K_1)\, [(j - H)\, L + (H - c)\, N]\Big\}/(LR - NP) \ldots (69)$$

Formulas for the flow nets can be obtained from (44) and (45) as described below (37).

Eq. (68) can be simplified. Subtracting and adding 1, - v, v^2, etc., to the terms in the series referred to in (68), and letting k → ∞, so that the last three terms in the series → 0, one has

$$\begin{aligned} M' = (1 - v)\; \Big(& \Big\{[\sinh 2\pi(h + b)/a]/[\cosh 2\pi(h + b)/a - X] - 1\Big\} \\ & + 1 - v \Big\{[\sinh 2\pi(3h + b)/a]/[\cosh 2\pi(3h + b)/a - X] - 1\Big\} \\ & - v + v^2 \Big\{[\sinh 2\pi(5h + b)/a]/[\cosh 2\pi(5h + b)/a - X] - 1\Big\} + v^2 - \ldots\Big) \end{aligned}$$

or recalling (1) and putting

$$\begin{aligned} M_1' = & \Big\{[\sinh 2\pi(h + b)/a]/[\cosh 2\pi(h + b)/a - \cos 2\pi x/a] - 1\Big\} \\ & - v \Big\{[\sinh 2\pi(3h + b)/a]/[\cosh 2\pi(3h + b)/a - \cos 2\pi x/a] - 1\Big\} \\ & + v^2 \Big\{[\sinh 2\pi(5h + b)/a]/[\cosh 2\pi(5h + b)/a - \cos 2\pi x/a] - 1\Big\} - \text{etc.} \;\ldots\ldots (70) \end{aligned}$$

and remembering that $1 - v + v^2 - \ldots = 1/(1 + v)$ there results

$$M' = (1 - v)\, [M_1' + 1/(1 + v)]$$

or using (3)

$$M' = (1 - v)\, M_1' + K_2/K_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (71)$$

The infinite series in (70) converges rapidly because the terms in braces and also their coefficients become smaller together, as the number of terms is increased. The series also converges for v = +1 and - 1.

It is desirable to have the denominator of the RHS of (66) and (69) (and (54) and (55)) in expanded form. From (51), (52), (64), and (65) the desired form is

$$LR - NP = L_1\, (b + s) - 4\pi b\, (b - r)/a + h\, (K_2/K_1)\, [4\pi(s - b + r)/a + L_1] \quad \ldots\ldots (72)$$

Formula for Q when in Figure 1B $K_1 = 0$--As a check on (66) let $K_1 \to 0$, that is, let $K_2/K_1 \to \infty$ or $v \to -1$. Then in the RHS of (72) the first two terms become negligible and (approximately)

$$(LR - NP)\,(K_2/K_1 \rightarrow \infty) = h\,(K_2/K_1)\,[4\pi(s - b + r)/a + L_1]$$

or using L_1 from (63) with $v = -1$

$$(LR - NP)\,(K_2/K_1 \rightarrow \infty) = h\,(K_2/K_1)\left\{4\pi(s + b)/a - 2\log_e 2 - \log_e[\cosh 2\pi(2b - r)/a - 1]\,(\cosh 2\pi r/a - 1)\right\} \qquad (73)$$

In view of (51) and (52), the numerator of (66) is

$$4\pi K_2\,[(j - H)\,P + (H - c)\,R]\,(K_2/K_1 \rightarrow \infty) = 4\pi K_2\,(j - c)\,hK_2/K_1 \qquad (74)$$

From (66), (74), and (73), and using $\cosh A - 1 = 2\sinh^2 A/2$, and since $Q(K_2/K_1 \rightarrow \infty) = Q(K_1 \rightarrow 0)$, one has finally

$$Q\,(K_1 \rightarrow 0) = 4\pi K_2\,(j - c)/\left\{4\pi(s + b)/a - 2\log_e 2 - 2\log_e \sinh \pi(2b - r)/a\,\sinh \pi r/a\right\} \qquad (75)$$

which is correct for $K_1 = 0$.

Eq. (75) serves as a check, because the same result can be derived in an independent (and quick) manner by considering only the array of drain tubes at $y = 0$ and the single image array at $y = 2d$. There is a further observation. In going from (73) and (74), to (75), the quantity h of Figure 1B cancels out. This is as it should be; for, if K_1 is zero in Figure 1B, the flow occurring below the layer of thickness h is not governed by the magnitude of h. A thin layer of sheet metal would serve as well as a thick layer of impervious clay. The compatability of the analytical results with this type of physical reasoning is evidence that the mathematical approach is sound.

Eq. (75) is of more interest than a check. The expression gives the seepage rate into drain tubes in waterlogged soil beneath an impervious layer, as possibly an airfield runway, beneath which there is artesian pressure and where the soil is uniformly permeable immediately up to the impermeable surface. The expression would not apply if a layer of sand were just below the impermeable surface.

Dropping of r in preceding results--In all the preceding equations the quantity r can be put equal to zero, except where r occurs in $\sinh \pi r/a$ and in $(\cosh 2\pi r/a - 1)$. The reason for putting r zero is not necessarily that r will be very small compared with d, s, b, $(h - d)$, $(2h - d)$, etc., these being terms generally associated linearly with r; but for the more subtle reason evident from work of KIRKHAM [1950, especially p. 659 and his footnotes 7 and 8]. Kirkham's paper shows that putting r zero, as described, simplifies computations and improves the accuracy of results. The question arises: Why then has r been kept in the analysis? The term r was kept because of its parallelism with $(-s)$, which could not be dropped. By keeping r, derivation of terms in $(-s)$ could be obtained by changing r to $(-s)$ in terms already derived for r; results could also be easily checked. Finally r has been retained because the results so given are exact (insofar as $s > a$) for drain tubes coinciding with lines of equal hydraulic head passing through the point $(x, y) = (0, r)$.

Results and discussion

Explicit expressions for the hydraulic head, the drain flow rate, and the rate of entry of water into the soil surface at any distance from a drain tube, have all been obtained for the situations indicated in Figure 1A and 1B. The hydraulic head μ_1, for a point (x, y) in the upper soil stratum of Figure 1A, is given by (11) in terms of the auxiliary quantities ϕ_1', A_1, and A_2, and the distance y. Here y is as shown in Figure 1A; and ϕ_1', A_1, and A_2 are defined by (5), (13), and (14). Symbols in the expression referred to in (5) are defined by (1), (2), (4), and Figure 1A. In (5) itself, v and n are defined by (2) and (4); d, a, and t by Figure 1A; and f_0' by (26). In (26), G, I, D, and F are given by (23), (24), (27), and (31) in terms of quantities in Figure 1A. The expression referred to in (27) contains symbols defined by Figure 1A and (2). In (11), A_1 and A_2 are defined, as has been stated, by (13) and (14). In (13) and (14), A_3 is given by (25). In (25), G, I, D, and F are as before.

The hydraulic head μ_2 for Figure 1A is given by (12); and the hydraulic heads ν_1 and ν_2 for Figure 1B, by (44) and (45). Auxiliary quantities for (12), (44), and (45) are defined ultimately by Figure 1A and 1B and (1), (2), (3), (4), and (38).

The quantity of water Q collected per unit time per unit length of drain tube is given for Figure 1A by (34), and for Figure 1B by (66), the same symbol Q being used for both figures. The amount of water Q' entering a unit area of soil at the soil surface per unit time is given by (37) for Figure 1A, and by (69) for Figure 1B, a single symbol again being used for Figure 1A and 1B.

The expressions for Q and Q' as just noted, although correct, are not usable for numerical work for the whole range of values $0 \lessgtr K_2/K_1 \lessgtr \infty$; because of slowness of convergence of certain infinite series. An infinite amount of time would be required to obtain numerical results for the practical case $K_2/K_1 = \infty$. Expressions conveniently usable (and dimensionless) for all values of K_2/K_1 can be obtained from the noted expressions for Q and Q' by: using (23), (24), (27), and (31) in (34) to obtain (76) below; using (13), (25), (26), (23), (24), (27), (31), and (36) in (37) to obtain (77) below; using (53), (51), (52), (72), (63), and (64) in (66) to obtain (80) below; using (71), (70), (53), (51), (52), (64), (63), (65), and (72) in (69) to obtain (81) below; simplifying results (terms in $(K_2/K_1)^2$ arising in (69) will cancel out); replacing (K_2/K_1) in resulting equations by $(1 - v)/(1 + v)$ in accordance with (3); dropping r compared with b, $h - d$, and larger terms; and finally multiplying resulting numerators and denominators through by $(1 + v)$. Stanley R. Petrick checked (76), (77), (80), and (81) below.

The results for Figure 1A are

$$Q/aK_1 = 4\pi \Big\{(1 - v)\,[(j - t - d)\,d/a + (t + d - c)\,h/a]$$

$$+ (1 + v)\,(t + d - c)\,(s - h + d)/a\Big\}/[(1 - v)\,(Dh - 4\pi d^2/a) + (1 + v)\,D\,(s - h + d)] \quad \ldots. (76)$$

$$Q'/K_1 = \Big((1 - v)\,\Big\{4\pi M\,[(j - t - d)\,d/a + (t + d - c)\,h/a] - (j - t - d)\,D - (t + d - c)\,4\pi d/a\Big\}$$

$$+ (1 + v)\,4\pi M\,(t + d - c)\,(s - h + d)/a\Big)/[(1 - v)\,(Dh - 4\pi d^2/a) + (1 + v)\,D\,(s - h + d)] \quad \ldots (77)$$

where

$$D = 2\Big\{\log_e\,(\sinh 2\pi d/a)/\sinh \pi r/a + v\,\log_e\,[(\sinh 2\pi h/a)/\sinh 2\pi(h - d)/a]$$

$$[(\sinh 2\pi h/a)/\sinh 2\pi\,(h + d)/a] - v^2\,\log_e\,[(\sinh 4\pi h/a)/\sinh 2\pi\,(2h - d)/a]$$

$$[(\sinh 4\pi h/a)/\sinh 2\pi\,(2h + d)/a] + v^3\,\log_e\,[(\sinh 6\pi h/a)/\sinh 2\pi\,(3h - d)/a]$$

$$[\sinh 6\pi h/a)/\sinh 2\pi(3h + d)/a] - \text{etc.}\Big\} \quad \ldots\ldots\ldots\ldots\ldots\ldots (78)$$

and

$$M = (\sinh 2\pi d/a)/(\cosh 2\pi d/a - \cos 2\pi x/a) + v\,\Big\{[\sinh 2\pi(2h - d)/a]/[\cosh 2\pi(2h - d)/a$$

$$- \cos 2\pi x/a] - [\sinh 2\pi(2h + d)/a]/[\cosh 2\pi(2h + d)/a - \cos 2\pi x/a]\Big\}$$

$$- v^2\,\Big\{[\sinh 2\pi(4h - d)/a]/[\cosh 2\pi(4h - d)/a - \cos 2\pi x/a]$$

$$- [\sinh 2\pi(4h + d)/a]/[\cosh 2\pi(4h + d)/a - \cos 2\pi x/a]\Big\} + \text{etc.} \quad \ldots\ldots\ldots (79)$$

The results for Figure 1B are

$$Q/aK_2 = 4\pi\,\Big\{(1 - v)\,h\,(j - c)/a + (1 + v)\,[(j - b - h - t)\,b/a$$

$$+ (b + h + t - c)\,(b + s)/a]\Big\}/\Big\{(1 - v)\,h[4\pi(s - b)/a + L_1] + (1 + v)\,[L_1\,(b + s) - 4\pi b^2/a]\Big\} \quad \ldots. (80)$$

$$Q'/K_1 = \Big\{(1 - v)\,[4\pi(1 - v)\,M_1'\,(j - c)\,h/a + 4\pi\,(j - c)\,b/a + 4\pi\,(b + h + t - c)\,(s - b)/a - (j - b - h - t)\,L_1]$$

$$+ 4\pi(1 - v^2)\,M_1'\,[(j - c)\,b/a + (b + h + t - c)\,s/a]\Big\}/\Big\{(1 - v)\,h\,[4\pi(s - b)/a + L_1]$$

$$+ (1 + v)\,[L_1\,(b + s) - 4\pi b^2/a]\Big\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (81)$$

where M_1' is given by (70)

$$L_1 = v\log_e(\cosh 4\pi b/a - 1) - \log_e(\cosh 2\pi r/a - 1) + (1 - v)\,(4\pi b/a - \log_e 2) + (1 - v^2)\,T \quad \ldots (82)$$

and

$$\begin{aligned} T = {} & \log_e [\cosh 4\pi(h + b)/a - 1]/(1/2) \exp 4\pi(h + b)/a \\ & - v \log_e [\cosh 4\pi(2h + b)/a - 1]/(1/2) \exp 4\pi(2h + b)/a \\ & + v^2 \log_e [\cosh 4\pi(3h + b)/a - 1]/(1/2) \exp 4\pi(3h + b)/a - \text{etc.} \quad \ldots\ldots\ldots (83) \end{aligned}$$

In the above expressions for Q and Q′ one needs the following results from (2)

$$(1 - v) = (2K_2/K_1)/(1 + K_2/K_1) \quad \ldots\ldots\ldots\ldots (84)$$

$$(1 + v) = 2/(1 + K_2/K_1) \quad \ldots\ldots\ldots\ldots (85)$$

$$(1 - v^2) = (4K_2/K_1)/(1 + K_2/K_1)^2 \quad \ldots\ldots\ldots\ldots (86)$$

As K_2/K_1 varies from 0 to ∞, (1 - v) varies from 0 to 2 and (1 + v) varies from 2 to 0. The advantage of the coefficients (1 - v) in (76), (77), etc., rather than K_2/K_1 now is clear.

As an aid in calculations one notices (the parentheses here meaning "function of") that

$$v(K_2/K_1) = -v(K_1/K_2) \quad \ldots\ldots\ldots\ldots (87)$$

The "etc." in (78), (79), (83), and (70) ((70) being needed in (81)) means that additional terms are to be added by inspection to the right hand sides of the equations, as many terms being added as are needed for the desired accuracy of results. The infinite series in (78), (79), (83), and (70) converge rapidly.

As a check on (76), (77), (80), and (81), one may put v = +1 and 0 corresponding to, $K_2/K_1 = 0$, and $K_1 = K_2$. The equations will go over into formulas of earlier work. Notice also that with $K_1 = K_2$ the RHS of (76) and (80) become equal, as do also the RHS of (77) and (81)--as they should. The special case v = -1, that is, $K_1/K_2 = 0$, was considered in the mathematical section. This case, practically speaking, might apply to artesian pressure under an impermeable surface, as an asphalt sheet over soil.

Some tables of results using (77) and (81) have been obtained; but these, and calculations of Q, will not be presented here, both for the sake of brevity and because a set of flow nets, to be presented, bring out interesting features of the theory. For numerical calculations with (76) - (87) it has been found that the BRITISH ASSOCIATION [1946] tables of $\sinh\pi x$ and $\cosh\pi x$ are admirably suitable. Values of $\exp\pi x$ can also be obtained from the British tables by use of $\sinh\pi x + \cosh\pi x = \exp\pi x$. Tables of values by Hayashi of $\exp\pi x$ are listed in FLETCHER, MILLER, and ROSENHEAD [1946], which tables, if used, should be checked.

Modifications when drain tube units are impervious except at joints--The results given above, are valid only if the drain tubes are completely pervious to flow. If water enters the tubes at joints, as in farm tile, the results should be modified. Let 2ϵ be the width of the joint, and let 2σ be the distance between successive (evenly spaced) joints. Then, for Q and Q′ in (76), (77), (80), and (81), the joint effect may be taken into account by adding to the RHS of (78) and (82), the expression $2\sigma^2/r\epsilon\pi^2)$ $(S_1 + S_2)$. Here S_1 and S_2 are given by KIRKHAM [1950, Eq. (20, 21)], his a to be changed to r, and his s to σ. The reason only (78) and (82) need be altered is that the joint correction is negligible (but not zero) in certain other terms, as one will see if he applies the methods of KIRKHAM [1950, especially p. 660] to the present problem.

If the drain tubes are perforated in the way described by KIRKHAM and SCHWAB [1951], then instead of the correction term in the last paragraph, one adds to the RHS of (78) and (82) a term πC, where C, not to be confused with C of (17), is given by Kirkham and Schwab's Eq. (7). The quantity πC takes into account the position and size of the perforations. Numerical values for C can be obtained with the aid of curves and an equation in another paper by SCHWAB and KIRKHAM [1951, Fig. 7 and Eq. (5)]. The present author made an error in the latter paper. The logarithmic term in Eq. (2) there should be preceded by $2/\pi$. Otherwise the equation will not yield the correct analytical result when the logarithmic term becomes infinite compared to the C-term.

The theoretical formulas (76), (77), (80), and (81), and others presented in the mathematical section, appear complex, especially if the joint corrections are taken into account. But when one considers that ten geometrical quantities, d, h, s, j, y, x, t, a, r, and c in the case of Figure 1A, and two soil constants K_1 and K_2 are involved, this is not surprising. (If joint and perforation effects are included, there are respectively two or three more geometrical quantities.) Despite the several variables, the results, as given here, permit straight-forward numerical work, functions no more complex, except in the case of joint or perforation effects, than hyperbolic functions, $\sinh x = (e^x - e^{-x})/2$ and $\cosh x = (e^x + e^{-x})/2$, being involved.

Flow nets--Probably the simplest way to present results, at least from a reader's viewpoint, is to show the flow nets corresponding to Figure 1A and B. One can obtain the lines of equal hydraulic head for the nets from values of μ_1, μ_2, ν_1, and ν_2 as given by (11), (12), (44), and (45). The streamline functions are derivable from μ_1, μ_2, ν_1, and ν_2, as indicated in earlier work [KIRKHAM, 1951]. Expressions for the stream functions have not been given here as they would take up too much space.

Four flow nets, Figures 2, 3, 4, and 5, have been prepared. To all four nets the following conditions apply. The upper stratum, indicated by "sand," is always more permeable than the lower stratum, indicated by "clay." This is the practical case of greatest interest. The drain tubes are of six-inch diameter (r = 0.25 ft) and are four feet deep to the drain axes. The artesian gravel is at 20-ft depth below the tubes. The tubes are spaced, for simplicity of calculations, at $20\pi/3$ ft = approximately 20 ft. The layer of ponded surface water is thin (t = 0 in Fig. 1). The hydraulic head in the drain tubes is 0.25 ft above the tube centers (tubes running full; c of Fig. 1 = 0.25 ft).

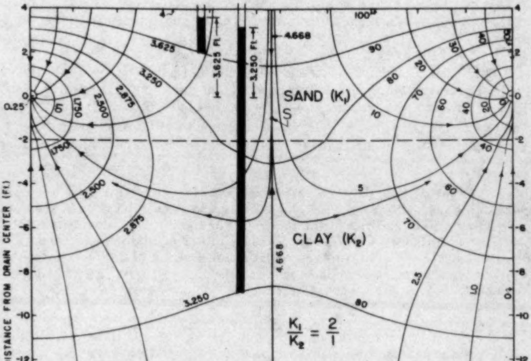

Fig. 2--Flow net corresponding to Figure 1A when c = 0.25, d = 4, h = 6, s = 20, j = 4, t = 0, r = 0.25, a = $20\pi/3$, all in feet, and $K_1/K_2 = 2$; the more permeable soil is designated "sand," the less permeable clay; two piezometers are indicated with water heights in them to scale; S is a point of stagnation

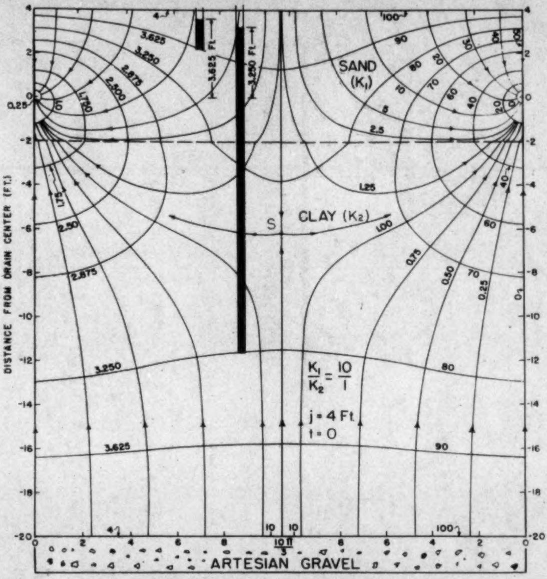

Fig. 3--Same as Figure 2 but with $K_1/K_2 = 10$

In the first three flow nets the drain tubes are in the upper more permeable soil; in the fourth, they are in the clay. The pressure in the artesian gravel in the first two flow nets is such that if a standpipe penetrated into the gravel, water in this pipe would stand to the level of the soil surface ($j = d = 4$ in Fig. 1). In the second two flow nets the standpipe water level would be ten feet above the soil surface ($j = 14$). The first two flow nets differ from each other only in the ratio K_1/K_2. This ratio is two for the first net and ten for the second. The last two flow nets differ from each other in that the drain tube in Figure 4 is in sand, and in Figure 5 is in clay, the thickness of the sand in the first case being six feet, in the second, three feet.

In all the flow nets the stream lines have been designated 50, 40, 30, . . ., 0. A streamline which enters vertically downward directly above the drain tube center is designated 50; the line entering vertically upward at the bottom of the tube is designated 0. As in previous papers, the difference between any pair of streamline numbers gives the percent of the flow between them. Thus (50 - 0) = 50 pct of the total flow, entering a drain tube, enters it from one side.

In the first three flow nets there is a stagnation point S on the vertical center line of the drawing. Here a downwardly directed streamline meets an upwardly directed one, to result in zero velocity. In the fourth flow net (Fig. 5) a point S is not shown, because near the center of the figure there is upward movement of water all the way to the soil surface.

In all four flow nets the lines of equal hydraulic head (equipotentials) are labelled in feet at the left-hand sides of the figures. The equipotential at the soil surface is in each case four feet, and at the drain tube, 0.25 ft. The value 0.25 ft is a consequence of the assumption that the drain tubes of radius 0.25 ft are running full but with zero back pressure or suction. As in other problems of this type the 0.25-ft equipotential does not, analytically, correspond precisely with the actual circular drain tube at all points on the tube. For practical purposes it does, as has become clear in the preceding section "Dropping of r in preceding results."

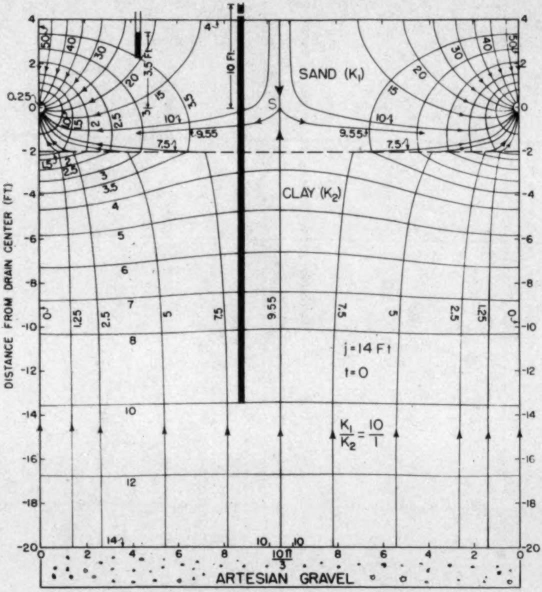

Fig. 4--Same as Figure 3 but with j = 14 ft; the streamlines in this figure correspond rather closely to those obtained experimentally by HARDING and WOOD [1942] in their Figure 2b

Piezometers are shown in the figures to indicate the physical significance of the lines of equal hydraulic head. For example, in Figure 2 a piezometer with its end on the 3.250 line has water standing in it to a height 3.250 ft above the drain tube centers. A piezometer on the 3.625-line has water standing in it to a height 3.625 ft above the drain centers. On the right-hand sides of Figures 2 and 3 (but not of Fig. 4 and 5) the equipotentials are also expressed in percent of undissipated effective head. The total effective head difference (4.00 - 0.25) ft is thus equivalent to 100 pct.

The flow nets bring out interesting features. The relative amount of water reaching the tubes directly from the artesian gravel and that coming from the soil surface can be read off directly. Thus, in Figure 2, where $K_1/K_2 = 2$, one sees that 4.668 × 2 = 9.336 pct of the water comes from the artesian gravel, and (50 - 4.668) × 2 = 90.664 pct from the ponded surface water. In Figure 3 where $K_1/K_2 = 10$, the values are respectively about two per cent and 98 pct. Thus increasing here K_1/K_2 five-fold, reduces the relative amount of artesian water to about 0.2.

Even in Figure 4, where $K_1/K_2 = 10$ and the artesian pressure in the gravel is ten feet above the soil surface (j = 14), there is still only 9.55 × 2 = 19.10 pct of the water reaching the tiles from the artesian gravel. But if the drain tubes are placed in the tighter subsoil, as in Figure 5, then, 24.16 × 2 = 48.32 pct of the flow passes from the artesian gravel directly into the drain tubes. Furthermore, (29.96 - 24.16) × 2 = 11.6 pct of the total water entering the drain tube passes from the artesian gravel directly to the soil surface. Thus one sees, upon comparing Figures 4 and 5, that if one is interested primarily in draining water from the surface soil, then drain tubes should be located in the upper (more permeable) stratum. Esther Chivers did most of the numerical work for the flow nets.

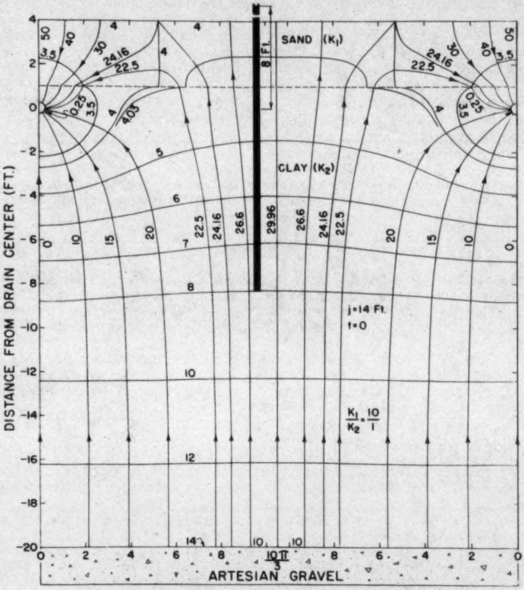

Fig. 5--Same as Figure 4 except that drain tubes are in the lower less permeable stratum (Fig. 1B) and the upper stratum is of thickness three feet rather than six feet

Comparison of theory with experiments--There are some experimental results which may be compared, as to general features, with the present theoretical results. HARDING and WOOD [1942] show in their Figure 2a and b streamlines of water seeping into drain tubes in stratified soil when the drain tubes are in the upper of two strata overlying artesian gravel. The streamlines are obtained in sand-tank models. Both surface and artesian water enter the tubes. In their Figure 2a the upper stratum is less permeable than the lower. But in their Figure 2b the situation is reversed and their streamline patterns may be compared with those shown in the present Figures 2, 3, and 4. In comparing, one should observe that the left-hand half of their Figure 2b corresponds to the right-hand half of the present Figures 2, 3, and 4, and vice versa. The present Figure 4 appears to compare most nearly with their Figure 2b. Both the figures have stagnation points at about the same level. Both show sharp refraction of the streamlines at the interface between the upper and lower strata.

An interesting special case--Suppose in Figure 1 that $K_2 = K_1$, and that $j = -s$. These values of the K's and j are not excluded because the theory is general. Suppose further that $t = 0$. Then one can verify that Q, of both (76) and (80), the quantity of water collected per unit length of drain tube, is zero. Analytically this statement means that no net water is collected by the drain tube. Water will seep into it in vertical streamlines immediately from above, and will seep out again in equal amount, again in vertical streamlines, immediately below. The theory thus shows (and it makes sense physically) that if there is unimpeded natural drainage, then drain tubes will serve no useful purpose once surface water has been removed. By unimpeded natural drainage is meant that water seeps vertically through the soil at a velocity equal to the hydraulic conductivity of the soil. This velocity is the fastest that water can move in the soil due to gravity. Only excess pressure, as with $t > 0$, or excess suction, as with the drains running full and discharging at a lower level than their general level in the soil, could make the velocity greater.

Limitations--There are two types of limitations on the results: analytical and physical. Analytically the distance s (Fig. 1) should be, according to (10), greater than about a or a/2, and r should be much smaller than s, a, d, and (h - d) or b. Practically speaking the limitation on r can be forgotten if r is not larger than d, (h - d), and b. Analytically the theory is valid for K_1/K_2 ranging between 0 and ∞, inclusive. Physically, K_1 and K_2 cannot both be infinite; nor can either K_1 or K_2 separately be infinite, if the drain tube is in the infinitely permeable medium. The reason is that Darcy's law, the validity of which has been assumed, would break down. Analytically t and j (Fig. 1) can range from 0 to ∞, inclusive. Physically they cannot, since then again Darcy's law would break down. The results are analytically correct for $j = -\infty$. The main point to remember in applying the results to practical situations is that the theoretical formulas can only be expected to apply insofar as the practical situation agrees with the situation indicated in Figure 1A or 1B.

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INFILTRATION AND AVAILABLE WATER STORAGE CAPACITY IN THE SOIL

K. G. Reinhart and R. E. Taylor

Abstract--Results of studies at Vicksburg, Mississippi, have emphasized the importance of antecedent available storage capacity upon infiltration rates and amounts for certain fine-textured soils. The recovery of infiltration rates after cessation of rainfall was found to be slow because of a corresponding slow rate of recovery of available storage. The value of electrical-resistance units, to follow the downward movement of water during infiltration runs and to determine the rate at which storage capacity became available after runs, was demonstrated.

Antecedent soil-moisture content has long been recognized as one of the important factors affecting infiltration rates of most soils. More to the point, it is the removal of soil moisture which makes storage space available for infiltered water and thereby increases the infiltration rate. Available storage capacity, or more simply "available storage," is the difference between the moisture content of the soil at any time and the maximum amount that can be held.

During the past two years a study involving measurement of infiltration rates, soil-moisture content, and available storage has thrown some light on their interrelationship. This study is part of a cooperative research project conducted at Vicksburg, Mississippi, by the Southern Forest Experiment Station of the U. S. Forest Service, and the Waterways Experiment Station of the Corps of Engineers.

Most of the data were obtained at two sites on the east bluff of the Mississippi River. One is an upland site with Loring silt loam on the upper and middle slope and Grenada silt loam on the lower slope; the dominant vegetation is wild barley, vetch, and Dallis grass. The other site is bottomland, with Collins silt loam supporting coneflower, wild barley, and Johnson grass. The upland soil is loess, while the surface soil of the bottomland site is alluvium derived from loess. All these soils are fine-textured and of low permeability.

The Rocky-Mountain infiltrometer [DORTIGNAC, 1951] was used for all infiltration runs. As a rule, a "dry" run made at prevailing field-moisture content was followed one to three days later by a "wet" run at the same plot location; runs were generally from two to four hours long. Artificial rainfall was applied at an average rate of five inches per hour and soil-moisture accretion and depletion were followed by gravimetric sampling. Fiberglas electrical-resistance units had been installed at each of the sites in order to obtain a daily record of soil-moisture content for use in a study of climatic factors and the soil-moisture regime.

The resulting data will be discussed under the following three headings: (a) the effect of available storage on infiltration rates and amounts, (b) available storage and recovery of infiltration rates between storms or parts of the same storm, and (c) the use of a soil-moisture record determined by electrical-resistance units to evaluate infiltration curves.

Effect of available storage on infiltration rates and amounts--Soil-moisture content and available storage have long been recognized as factors affecting infiltration. COOK [1946] observed that it is commonly assumed that degree of wetness of an area prior to rainfall is the controlling factor of initial infiltration capacity. LASSEN and LULL [1951] noted that as a soil becomes saturated and its pores are filled, percolation and infiltration rates will be reduced. NEAL [1938] stated that initial soil-moisture content had a greater effect on infiltration capacity during the first 20 minutes of rainfall than any other factor. SHERMAN and MUSGRAVE [1942] pointed out that reductions in infiltration occur in winter because of soil-moisture increase.

SHARP, HOLTAN, and MUSGRAVE [1949] found on 54 plots in Illinois that soil-moisture content was significantly related to mass infiltration; these tests were on a claypan soil. SCHIFF and DREIBELBIS [1949ab] in a very thorough study, worked out the relationships between infiltration, transmission and percolation rates, and available storage for Keene and Muskingum silt loams in Ohio. WHELAN, MILLER, and CAVALLERO [1952] accounted for soil-moisture storage in their method for determining surface runoff by routing infiltrated water through the profile. Additional information is still required as regards both the interrelationships of moisture content, available storage, and infiltration for different soil types and conditions, and procedures for their measurement.

At Vicksburg, the strong influence of available storage on infiltration became evident when infiltration curves for several sites obtained in late spring were studied in conjunction with a daily soil-moisture record. Accretion from natural rainfall determined from the soil-moisture record was in general agreement with that estimated by applying the infiltration curves to intensity records of storms that occurred during the period of infiltration tests. When analysis was made of summer storms, however, it was found that accretion was greater than the amount estimated by applying the spring-determined curves.

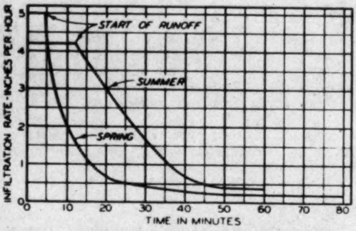

Fig. 1--Average infiltration curves for spring and summer dry runs on lower slope of the upland site

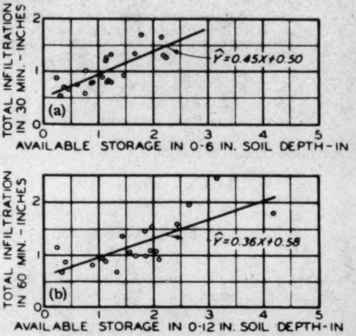

Fig. 2--Relation of total infiltration and antecedent available storage for dry runs at the upland site

A second series of infiltration tests was therefore made in late summer at the upland site. Infiltration rates for dry runs were much higher than those of the previous spring (Fig. 1). When these rates were applied to summer storms, much closer agreement was obtained between computed and actual soil-moisture accretion.

Data for the upland site were analyzed to determine the extent to which available storage affected infiltration. Figure 2a shows the relationship between available storage of the surface six inches of soil and total infiltration during the first 30 minutes of dry runs; the correlation coefficient is 0.79. Figure 2b shows the relationship of available storage in the surface 12 inches of soil to total infiltration in the first 60 minutes of runs; the correlation coefficient is 0.75.

The amount of infiltration into a soil column of a given depth is equivalent to the amount of water percolating through the column, and, in addition, the amount retained within the column. This latter amount is limited by the available storage. Regardless of antecedent moisture conditions, the infiltration rate curve levels off at approximately the same value, as shown in Figure 1. However, the lower the initial soil-moisture content, and thus the more storage available, the longer it will be before this low, steady value is reached. The importance of available storage is greatest in those soils having a low percolation rate and surface conditions which favor infiltration.

Low infiltration rates, despite a vigorous herbaceous cover, and shallow depths of wetting at both the upland and bottomland sites lead to the conclusion that low permeability and available storage are the two factors most important in determining infiltration for these soils and conditions. The antecedent available storage is of importance during the initial period of relatively high rates (of great importance for the first half hour, of lesser importance in the second half hour, Fig. 1). Thereafter, the rate is governed by the low permeability of the soil. The rate at which water can enter the soil is of importance for only a very short time at the beginning of the run when entry of water into storage permits higher infiltration rates.

Available storage and recovery of infiltration rate--Infiltration curves are usually developed from artificial rainfall tests in which water is continuously applied at a rate sufficient to cause runoff. Application of the curves is complicated because natural rainfall never occurs in such an orderly manner. The difficulty lies in determining the proper infiltration rate to apply after breaks in the storm or after periods of intensities insufficient to produce runoff. COOK [1946], defining infiltration capacity as the rate at which infiltration would take place at any instant if rainfall were applied in excess, devised a method of determining its value. His method is based upon the premise that infiltration capacity at any instant depends upon the amount of infiltration that has occurred up to that instant. SCHIFF and DREIBELBIS [1949b] pointed out that when rain begins to fall again after a break in the storm, the infiltration rate will be based on the storage space at the time.

Infiltration recovery was investigated in a series of infiltration tests in late summer at the upland site. During these tests, two periods of rainfall application were separated by a drying period of one to four hours.

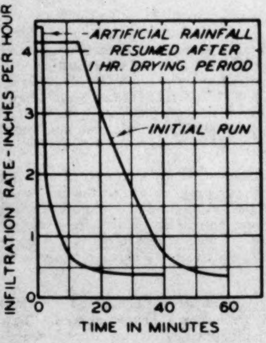

Fig. 3--Average infiltration curves showing recovery of infiltration rate after one hour of drying on lower slope of the upland site

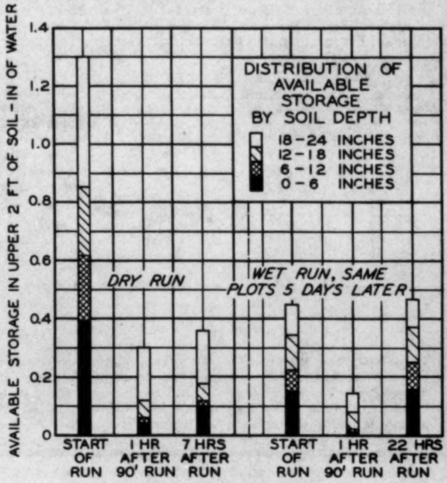

Fig. 4--Available storage before and after infiltrometer runs at the bottomland site

On two plots, rainfall was applied with soil at field-moisture content and continued until the infiltration curve levelled off; after a one-hour drying period rainfall was again applied. The average curves for the two plots (Fig. 3) indicate that the infiltration rate recovered during the drying period and exceeded the final rate of the initial run for about ten minutes.

Runs were also made with drying periods of two and four hours. In both cases the infiltration rate after the break apparently exceeded that just before the break for about ten minutes.

Figure 4 shows available storage before and after two runs at the bottomland site in December. Natural rains interrupted the drying periods after 7 and 22 hours. Available storage recovered only 0.06 inch in seven hours after the first run (it was at a minimum one hour after the end of the run rather than immediately after the run). In the second run, available storage recovered 0.32 inch in 22 hours after the run, so that it was approximately equal to storage before the run.

The recovery of available storage after the completion of runs was quite slow. Referring to Figure 3, the high infiltration rate prevailing for ten minutes after the drying period indicates only about 0.25 inch of infiltration in excess of the amount that would have occurred had the rate at the end of the initial run prevailed. This apparent increase in infiltration is probably largely due to a recovery of opportunity for interception and depression storage, as the curves have not been corrected for these factors. With two- and four-hour breaks the amount of added infiltration, or apparent infiltration, is very little more. The recovery of 0.32 inch of available storage in the soil at the bottomland site means that this amount of additional actual infiltration could occur before the infiltration rate in a new rainfall period would fall to the level of the rate at the end of the run.

Use of soil-moisture records to evaluate infiltration curves--A study of rainfall records and soil-moisture content before and after a number of storms was made to determine whether the rainfall rate exceeded the infiltration rate. It was on this basis that spring infiltration curves were found to be inapplicable to summer conditions. However, surface or subsurface flow from adjacent areas resulted in more soil-moisture increase than rainfall for some storms and prevented a proper comparison.

In December, 1952, 90-minute dry and wet infiltration runs were made over the soil-moisture unit installations at the bottomland site. The following data for a dry run computed from the soil-moisture record show, for different soil depths, the total accretion and the elapsed time from the start of the run to start of appreciable wetting, as shown in Table 1.

Table 1--Data on moisture accretion

Soil depth	Accretion	Time of wetting
inch	inch	minute
0 - 3	0.16	15
3 - 6	0.18	45
6 - 9	0.10	45
9 - 12	0.11	45
12 - 18	0.16	80
18 - 24	0.08	95
24 - 48	0.00	....
Total	0.79	

Rainfall applied with the infiltrometer was 5.56 inches; runoff amounted to 4.68 inches leaving 0.88 inch for interception and infiltration. Interception was estimated at 0.10 inch resulting in 0.78 inch of infiltration for the entire run as compared with the 0.79 inch from the soil-moisture record. Figure 4, already presented, shows the status of available storage before and after these runs.

Table 1 demonstrates the downward percolation of water as the run progressed and the agreement between total infiltration and soil-moisture accretion. Water penetrated less than two feet into the soil. The infiltration rate fell to below one-half inch per hour before the end of the runs because of the exhaustion of available storage space in the upper layers and the low permeability of the soil.

These tests were exploratory. They might have been more informative if conducted at a time when more storage was available and, consequently, more infiltration would have occurred. They demonstrate the possibilities of using soil-moisture records determined by electrical-resistance units rather than prove their utility or provide a detailed procedure for further studies. This approach is feasible only when the soil-moisture record includes the full depth of moisture penetration. For the soils studied, the relationship between amount of accretion and amount of infiltration is generally good. Even though variation in wetting from point to point may prevent balancing out precise calculations, considerably more can be learned than in the usual infiltration run where no data are secured as to the disposition of the infiltered water.

Acknowledgment--Part of the analysis of data and supervision of much of the field work reported herein was by E. J. Dortignac, formerly in charge of this Project.

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SOME NOTES ON THE RELATION OF GROUND-WATER LEVELS TO POND LEVELS IN LIMESTONE SINKS OF SOUTHWESTERN GEORGIA

E. L. Hendricks

Abstract--Records of water levels in limesink ponds in southwestern Georgia and of water-table levels in the vicinity of these ponds are used to demonstrate: (1) some ponds with highly impermeable beds are virtually unaffected by water-table levels, except when water-table levels are above the rim of the impervious materials; (2) interchange of water between pond and water table occurs when beds are relatively permeable. Three phases in the relation between pond level and water-table level are recognized: (1) water-table level higher than pond level causing ground-water flow into the pond; (2) ground-water level below pond level but in direct contact with it and measurably controlling rate of seepage from the pond; (3) ground-water level below pond level but not in direct contact with it and not appreciably controlling rate of seepage from the pond. In phase (3) the water table has a perceptible mound at a point underneath the pond.

Introduction--In another paper [HENDRICKS and GOODWIN, 1952] some factors related to variations in pond levels in limesink ponds in southwestern Georgia were discussed. This paper amplifies the portion of the study concerned with the relation between pond levels and ground-water levels. Description of the area in which the study was conducted, of the ponds from which data were obtained, and the methods used in making measurements are inclosed in the other report.

It is sufficient to say here that the limesink ponds in this area lie in rather shallow depressions on the surface of a residuum of unsorted sands and clays ranging from 70 to 100 ft in thickness. Beneath the residuum are undissolved remnants of Oligocene and Eocene limestones. It is believed that the limesinks result from collapse of the overburden when the remnants of the deep limestones covered by the residuum are dissolved. The youngest of these depressions have rather pervious bottoms and contain water intermittently. Bottoms of the older depressions are covered by relatively impervious sediments, which are characteristically thicker in the deeper parts and grade to knife-edge proportions at higher elevations on the boundary slopes.

Thirteen ponds were investigated. These are in relatively old limesinks and contain heavy growths of vegetation. Water-level measurements were made in ponds by weekly observations of staff gages; in eight-inch shallow bored wells near the ponds measurements were obtained with steel tapes. In some instances, records were obtained from recorders. All elevations were expressed in terms of sea-level datum.

The wells used in this study only partially penetrate the residuum and are, except for those noted, open-hole wells. Thus water levels in these wells reflect water-table elevations in the residuum. A short period of record from two wells side by side, one open-hole in the residuum and the other cased and penetrating into the underlying limestones, showed water levels in the two strata to be different by amounts varying from a few tenths of a foot to a few feet. The degree of correlation between water-table and artesian levels has not been established.

It is the purpose of this paper to present graphically, without mathematical development or interpretation, the relationships between pond levels and water levels in shallow wells which are superficially apparent from the data at hand.

General relations of pond levels to ground-water levels--Hydrographs for three representative ponds and nearby observation wells for the period 1940 to 1948 are shown in Figure 1. In these ponds, the water level was above the water table during the greater part of each year; for 99 pct, 93 pct, and 63 pct of the period of record at Ponds 1, 4, and 12 respectively. Ground-water levels ranged from 22 ft below pond level to 0.4 ft above pond level for Pond 1 during the period, except following an extraordinary flood in 1948. Ground-water levels at Pond 4 ranged from ten feet below to 1.9 ft above pond level and at Pond 12 from 18 ft below to 3.6 ft above pond level.

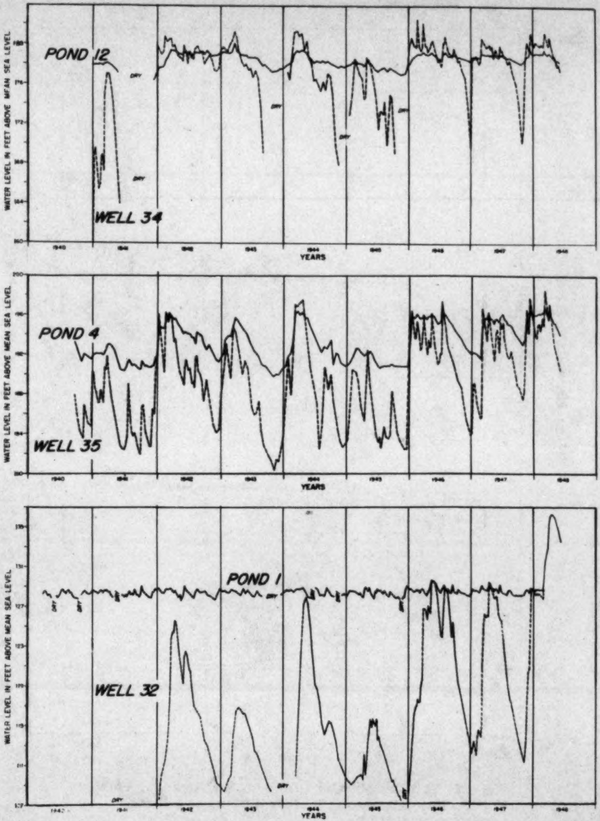

Fig. 1--Water levels in Ponds 1, 4, and 12 and in nearby observation wells, 1940 to 1948

The variable relations of pond and ground-water levels are shown by the following examples:

Profiles of ground-water level across Pond 15 on four different dates are shown in Figure 2. This pond is dry for a long period each year and the bottom appears to be more pervious than in any of the other ponds observed. Water-level measurements were made in three observation wells located on a line that extends across this pond. Wells bored with eight-inch augers are located on opposite banks and the third (Well 60) is in the pond. The latter is cased with a two-inch iron pipe to prevent pond water from flowing directly into the well and terminates about ten feet below the pond bottom.

The profile for April 8, 1943, illustrates a condition under which the ground-water level on both sides of the pond was above pond level. The pond level observed was about 1.1 ft below the ground-water level. The level in Well 60, the one in the pond, was one foot above the pond and only

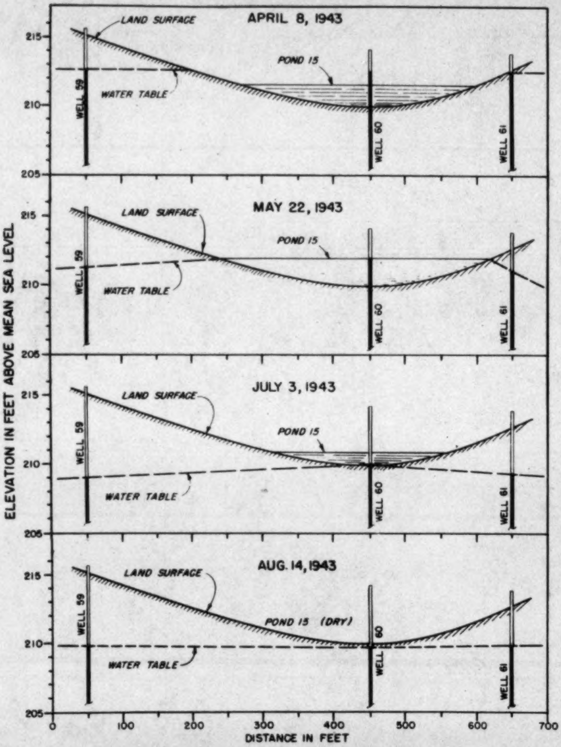

Fig. 2--Profiles of water levels in Pond 15 and in related observation wells for four different conditions

0.1 ft lower than the level in the two wells on the bank. This indicates an upward hydraulic gradient of one foot between the bottom of Well 60 and the pond bottom to cause seepage of ground water into the pond. The pond level being below ground-water level indicates that this seepage was not as great as evapotranspiration losses from the pond.

The profile for May 22, 1943, illustrates condition when the water table, as indicated by Wells 59 and 61, was below pond level. At this time water in Well 60 was at essentially the same level as the pond. Apparently there was enough seepage from the pond at that time to produce a mound in the water table. Inasmuch as the ponded area was great enough for the marginal areas to lie over the more pervious bottom materials it seems probable that the whole pond area was in contact with the water table.

The profile for July 3, 1943, indicates conditions after a further recession of both pond and ground-water levels. The level of water in Well 60 was just above the bottom of the pond and 0.85 ft below the pond level. Seepage from the pond was apparently enough to produce a mound in the water table on this date also. Although it cannot be proved on the basis of available data, it appears probable that seepage was insufficient to bring more than a portion of the pond bottom in contact with the water table. By August 14, 1943, the pond was dry and, consequently, had no effect on the water table.

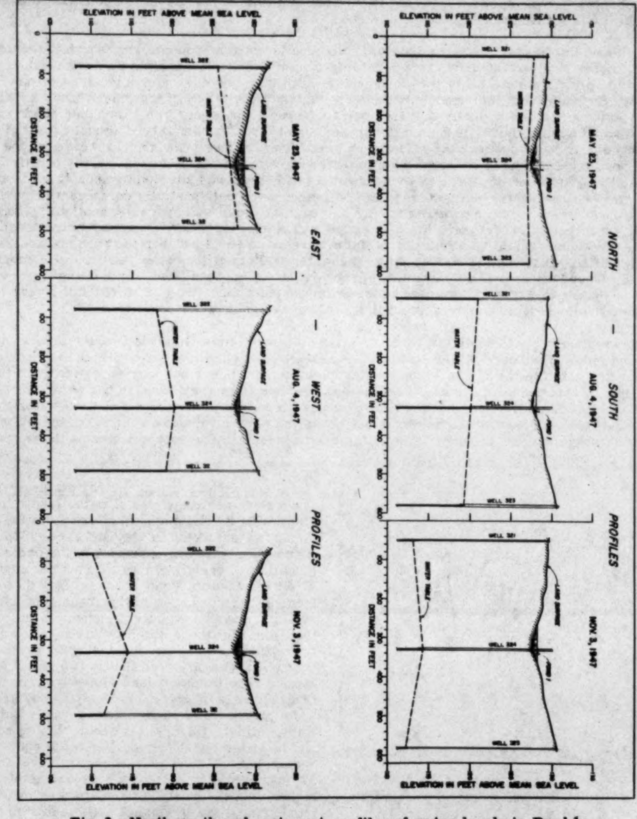

Fig. 3--North-south and east-west profiles of water levels in Pond 1 and of ground-water levels on three representative days

Figure 3 shows north-south and east-west profiles of ground-water level and pond level in the vicinity of Pond 1 on three representative days. Wells 32, 321, 322, and 323 are eight-inch open-hole observation wells located on the tributary land slopes. Well 324 is cased and terminates about 20 ft below the pond bottom. The profiles for May 23, 1947, in Figure 3, illustrate an above-average, but not extremely high, ground-water level. The water level in Well 32 was observed to be above pond level only about one per cent of the time. The profiles for August 4 and November 3, 1947, indicate low, but not unusual, ground-water levels. These later profiles indicate a definite mound in the water table attributable to seepage from the pond. Water levels in the wells on May 23 did not reflect the existence of a mound on that date. The water levels on August 4 and November 3 do not admit the possibility of hydraulic continuity between the pond and the water table on those dates. On May 23, however, there may have been a mound in contact with the pond but not reflected in the observed level in Well 324 owing to the fact that this well reflects the potential at a point about 20 ft below the water table.

A mound in the water table underneath this pond is usually evident even though the bottom materials are highly resistant to flow. In tests run on a disturbed sample by the Bureau of Public Roads the specific permeability was found to be 0.005 inch per day under a gradient of one foot per foot. Seepage from this pond is believed to be less than in any of the others studied. As seepage is evident here, it is likely that loss due to seepage may occur in all the other ponds in the area. Except during unusually high water-table conditions, which will be discussed later, Pond 1 does not appear to be appreciably affected by ground-water level. In Pond 15, however, the relation of pond level and ground-water level is different, as shown in Figure 2. In the profile for April 8, 1943, for Pond 15, there is evidence that pond stage was affected by accretions from ground-water flow although evapotranspiration losses were only partially compensated by effluent ground-water seepage. The profile for May 22 suggests there was hydraulic continuity and that the rate of recession of the pond due to seepage was being controlled by ground-water level. Here the rate of seepage would be a function of the difference in level between the pond and the water table [MUSKAT, 1937, pp. 346-353]. After the water table recedes below the point of contact with the pond, ground water probably has little practical effect on pond level. Under conditions as pictured for Pond 1 in Figure 3, seepage water from the pond merely moves through the permeable bed above the deep-lying water table until it reaches the ground-water surface.

These examples illustrate the three relations observed between ground-water levels and pond levels, namely: (1) Ground-water level may be higher than pond level, a condition that causes ground water to flow into the pond. (2) Ground-water level may be below but near enough to pond level so that seepage from the pond creates a continuous gradient from pond level to the water table. The rate of seepage from the pond is then controlled by ground-water level. (3) Ground water may be below pond level and seepage through the bottom of the pond may cause a mound in the water table but rate of seepage from the pond is not influenced appreciably by ground water as the water table is not in contact with the pond.

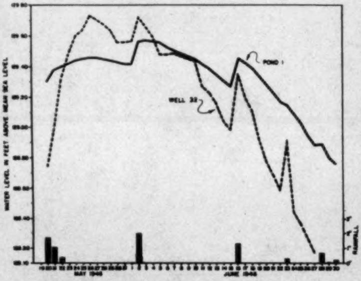

Fig. 4--Hydrographs of water levels in Pond 1 and Well 32, and bar graph of precipitation, May-June, 1946

Some details of high-stage relations--Figure 4 shows hydrographs of water levels in Pond 1 and Well 32 and amounts of precipitation during a high-water period in May and June, 1946. This figure illustrates an exception to the ordinary condition where ground water does not appreciably affect the level of Pond 1. From May 23 to 27 the stage of the pond rose in the absence of additional rainfall, and thorough field inspection in the area indicated that there was no surface inflow during the period. Pond rise was caused by ground-water inflow. It was observed that in two small depressions on the tributary land slopes west of the pond (Fig. 5) pools of water, obviously fed by ground water, were overflowing into the pond. This spring flow continued for several weeks, during both rise and recession of the pond. While the pond was receding, May 27 to June 1, the water level in Well 32, upgradient from the pond, remained at a level higher than the pond. As explained below, inflow from ground water was not sufficient to prevent recession of the pond.

Some details of water-table levels near Pond 1 during the period May 23 to June 1, 1946, are shown in Figures 6 and 7. During the high-water period of May-June, 1946, a number of temporary open-hole wells were bored on the tributary land slopes and observations of ground-water levels were made from which ground-water contours were developed. Figure 5 shows the approximate land contours in the vicinity of Pond 1, and Figures 6 and 7 show the approximate water-table contours on June 13 and June 24, respectively. The pond was in recession on both of these dates.

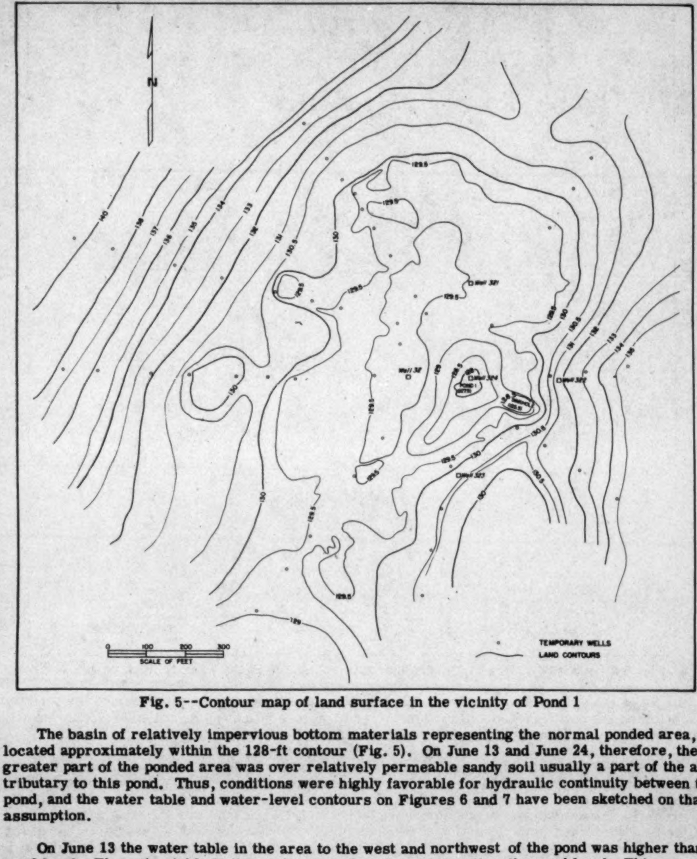

Fig. 5--Contour map of land surface in the vicinity of Pond 1

The basin of relatively impervious bottom materials representing the normal ponded area, is located approximately within the 128-ft contour (Fig. 5). On June 13 and June 24, therefore, the greater part of the ponded area was over relatively permeable sandy soil usually a part of the area tributary to this pond. Thus, conditions were highly favorable for hydraulic continuity between the pond, and the water table and water-level contours on Figures 6 and 7 have been sketched on that assumption.

On June 13 the water table in the area to the west and northwest of the pond was higher than pond level. The water table to the east and southeast was lower than the pond level. This suggests that at this time ground water was flowing into the pond from the west and northwest, and water was flowing out of the pond into ground water to the east and southeast. This is the general direction of drainage to the Flint River, approximately two and a half miles to the southeast. The fact that the pond was in recession indicates that ground-water inflow was not as great as combined ground-water outflow and losses by evapotranspiration. On the other hand, the period May 23-27 (Fig. 4) demonstrates that at times effluent ground-water seepage may exceed outflow and evapotranspiration losses.

Figure 7 shows the ground-water contours on June 24 after further pond recession. Water level in the pond was higher than the water table at all points on the periphery of the pond. The shape of the contours for which there is good definition indicates that seepage was creating a mound

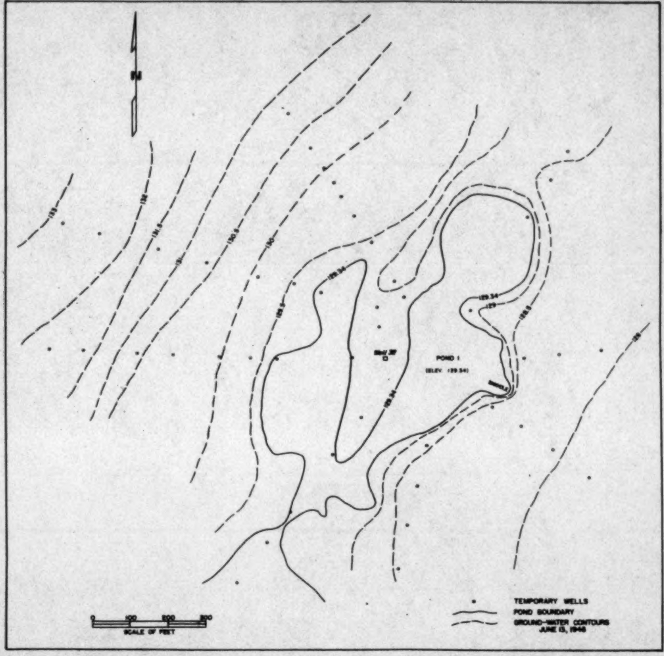

Fig. 6--Boundary of Pond 1 and ground-water contours in the vicinity on June 13, 1946

in the water table on June 24. Although water-table elevations near the periphery of the pond were not obtained in great enough detail to determine hydraulic continuity, for the same reason as cited for June 13, it seems probable that there was continuity on June 24 also.

In Figure 8, water levels in Pond 1 minus the ground-water levels in Well 32 are plotted against the daily change in pond stage (not corrected for indeterminate evapotranspiration losses) for days not affected by current rainfall during the high-water period May-June, 1946. The distribution of points in Figure 8a indicates that under these high water-table conditions the rate of seepage out of the pond is related to the elevation of the water table and that the rate of seepage is increased as the water table recedes to greater distances below pond level. The general nature of this relationship is in agreement with the functional relations proposed by MUSKAT [1937, pp. 346-353] for seepage from streams and canals which merge with shallow water tables and argues strongly in favor of the assumptions previously made for hydraulic continuity between this pond and the water table when the water table is high. On the other hand, Figure 8b, which is a similar plotting for periods in February, March, November, and December, 1947, when ground-water level was several feet below pond level, demonstrates that during those periods there was no recognizable relation between seepage rate and ground-water level. The logical conclusion, therefore, is that during those periods seepage was insufficient to create a water-table mound high enough to produce hydraulic continuity.

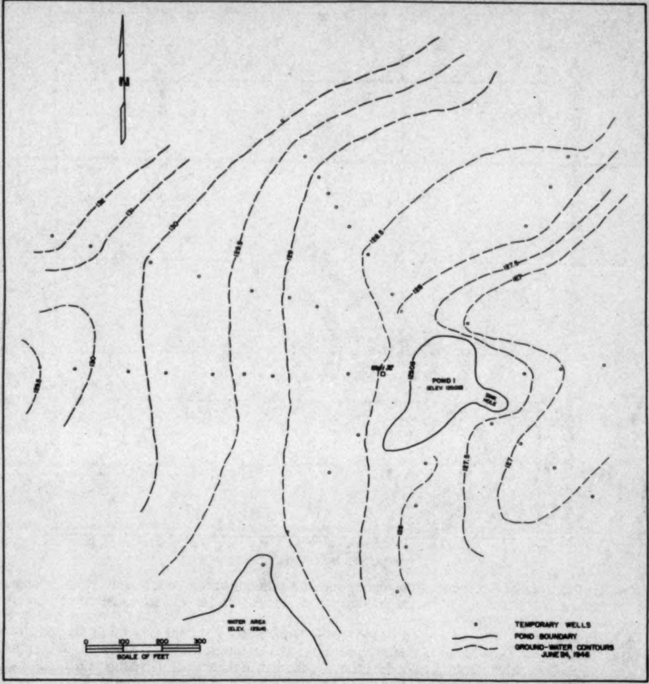

Fig. 7--Boundary of Pond 1 and ground-water contours in the vicinity on June 24, 1946

Summary and conclusions--Hydrographs of pond levels in three representative limesink ponds in southwest Georgia were compared with hydrographs of ground-water levels in nearby observation wells. Water levels in the three ponds were above ground-water levels approximately 99 pct, 93 pct, and 63 pct of the time during the seven and a half years of record. Ground-water profiles and pond levels were compared for two ponds. It was shown: (1) Pond level may be lower than the water table owing to the resistance to effluent seepage through the pond bottom. (2) Although the pond bottoms are usually relatively impervious, a demonstrable mound in the water table is created by seepage from some of the ponds. (3) Three phases in the relation between ground-water levels and pond levels are demonstrable: (a) Ground-water level may be higher than pond level, which may cause ground water to flow into the pond. Sometimes this effluent seepage is not as great as evapotranspiration losses from the pond. When the water-table profile intersects a pond surface, the pond may be both influent and effluent at the same time. (b) Ground-water level may be below pond level but still measurably control the rate of seepage from the pond if hydraulic continuity exists. (c) Ground water may be below the pond level and seepage from the pond may cause a mound in the water table, but the rate of seepage from the pond is not appreciably influenced by ground water because of the lack of hydraulic continuity.

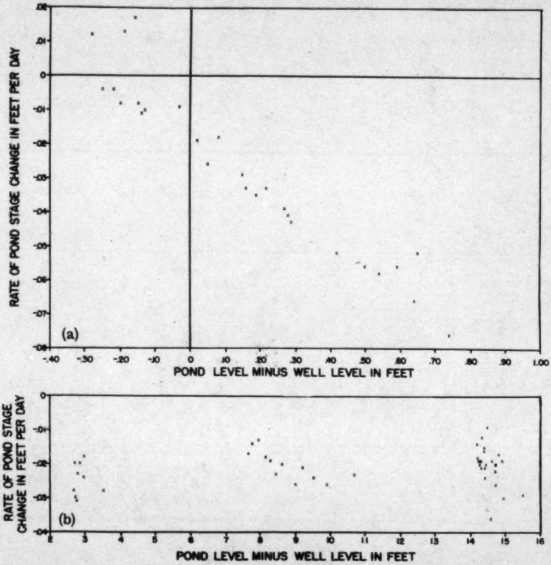

Fig. 8--Plottings of differences between pond and ground-water levels against daily change in stage of Pond 1; (a) for high ground-water levels; (b) for low ground-water levels

Acknowledgment--This is a joint contribution from Emory University Field Station, Newton, Georgia; the Georgia Department of Mines, Mining, and Geology, Atlanta, Georgia; Water Resources Division, U. S. Geological Survey, Washington, D. C.; and Entomology Division, Communicable Disease Center, Public Health Service, Federal Security Agency, Atlanta, Georgia.

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A NEW FORMULA FOR FLOW INTO PARTIALLY PENETRATING WELLS IN AQUIFERS

Wen Hsiung Li, Paul Bock, and George S. Benton

Abstract--The relation between drawdown and yield in an aquifer due to pumping from a partially penetrating well is approached experimentally, employing the analogy between the flow of electricity and the flow of fluids through porous media. It is found that, except for a small area near the well, the drawdown curve of a partially penetrating well has the same shape as that of a fully penetrating well. Outside this small area near the well, the two drawdown curves differ by a constant magnitude which can be found from a simple empirical formula obtained from the experimental data.

Introduction--Due to its great practical interest to engineers, the problem of well flow has been analyzed by many investigators. The flow into gravity wells was first treated by DUPUIT [1863], and since then many other papers have been written on this subject.

In the present paper a somewhat different problem is considered: the flow of water under pressure into a well from an aquifer, as shown in Figure 1. When the well penetrates the whole thickness of the aquifer, the flow is relatively simple. For the ideal case of an aquifer of homogeneous and isotropic material and of uniform thickness, the flow into a fully penetrating well is radial and the drawdown of the piezometric surface can be found from

$$\frac{dh}{dr} = \frac{Q}{2\pi KDr} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where K is the coefficient of permeability (dimensionally, length per unit time) of the aquifer material for the fluid under consideration.

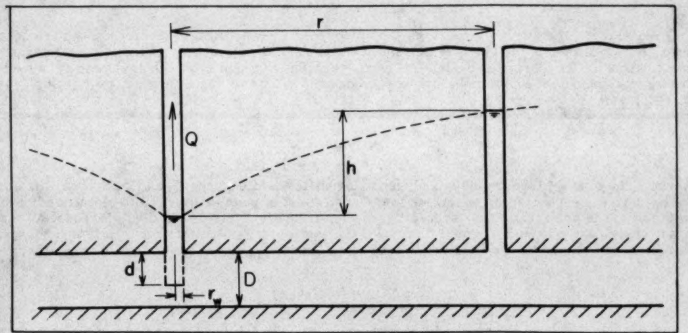

Fig. 1--Flow into a partially penetrating well

On the other hand, the flow into a partially penetrating well is much more involved as the flow near the well is no longer radial. An approximate solution of this problem by MUSKAT [1937, p. 274], while mathematically elegant, is too complicated for practical use. A more simple solution was advanced by KOZENY [1933] and has been used widely in practice. In terms of the symbols shown in Figure 1, this formula is

$$Q = \frac{2\pi Khd}{\log_e(r/r_w)}\left(1+7\sqrt{\frac{r_w}{2d}}\cos\frac{\pi d}{2D}\right) \quad \ldots\ldots\ldots\ldots\ldots \text{(2)}$$

Although Kozeny's formula yields reasonable results in practice, it has certain limitations. Since the flow is essentially radial beyond a certain distance from the well, a formula for partially penetrating wells should satisfy (1) for large values of r. This is not true of Kozeny's formula. Clearly, a further investigation of the problem is warranted.

In the present study, the analogy between the flow of electricity and seepage through porous media is employed. The idealized aquifer chosen for study may be described as follows: (1) The aquifer is horizontal and of uniform thickness. (2) The aquifer is composed of homogeneous and isotropic material. (3) There is no flow across the interfaces between the aquifer and the aquicludes. (4) The aquifer is of sufficient areal extent so that the effects of boundaries can be neglected. (5) Steady-state conditions are established over a large area around the well.

The degree of validity of the first four assumptions depends on the particular field conditions. The last assumption is valid some time after the beginning of pumping. When pumping is started, the flow into the well comes from the immediate neighborhood of the well, accompanied by compression of the aquifer near the well. However, the rate of deformation there rapidly decreases, and additional compression takes place only at a large distance from the well.

With these simplifications, the problem reduces itself to finding the relation between the drawdown and the discharge in an axial-symmetrical steady-state flow system. In the present study, the losses of energy through the well-screen and in the well are not considered. Although the hydraulic head in the aquifer is distributed three-dimensionally, a distance h can be defined which is a function only of the radial distance from the well. As shown in Figure 1, this quantity is the difference in hydraulic head between an arbitrary point at the top of the aquifer and at the well. The difference in head h (r) is thus uniquely determined by the drawdown in the piezometric surface indicated by a test well just penetrating the top of the aquifer. The problem is to find the relationship between the shape of this piezometric surface, the discharge, and the degree of penetration of the well. Assuming that the flow follows Darcy's Law, it can be shown by dimensional analysis that this is equivalent to determining the explicit functional relationship

$$\frac{KDh}{Q} = f\left(\frac{D}{d}, \frac{r}{r_w}, \frac{D}{r_w}\right)$$

Model and apparatus--By means of the analogy between the flow of electricity and seepage through porous media, the function expressed above may be obtained empirically by using a geometrically similar electrical model. A conductor is used to represent the aquifer, and two electrodes to represent the well and a surface of constant hydraulic head. By analogy, MUSKAT [1937, p. 140] gives

$$\frac{KDh}{Q} = \frac{\sigma DV}{I}$$

where I, the current through the model, is analogous to the discharge Q, and σ, the specific conductivity of the conductor, is analogous to the coefficient of permeability. The electric potential in the model is analogous to the hydraulic head in the aquifer. Since h is the difference in hydraulic head between the well and a point at the top of the aquifer, the potential drop V corresponding to h is measured between the well electrode and a point on the top of the conductor. Thus in the model

$$\frac{\sigma DV}{I} = f\left(\frac{D}{d}, \frac{r}{r_w}, \frac{D}{r_w}\right)$$

The apparatus used for measuring the various quantities involved in the problem consists of three components: (1) a tank with a solution of common salt as the model, (2) a potentiometer-bridge instrument, and (3) an audio-frequency generator. Alternating current is used to minimize polarization at the electrodes.

The tank is constructed of Plexiglass, assembled to form a sector of 18°, with sides 33 inches long and six inches high. Brass rods of various diameters, filed to 18° sectors, are used as the well-electrode at the apex of the tank. A copper plate, 1/16 inch in thickness, is used for the electrode at the other end of the tank. This plate is placed vertically since, from existing data, MUSKAT [1937, p. 270], it is known that, at a distance from the well greater than twice the thickness of the aquifer, the flow is essentially two-dimensional, and the equipotential surfaces are practically vertical cylindrical surfaces.

Figure 2 shows the schematic diagram of the audio-frequency generator. It is used to produce a tone of approximately 1000 cps in the head-phones. A control for varying the output is incorporated in the circuit.

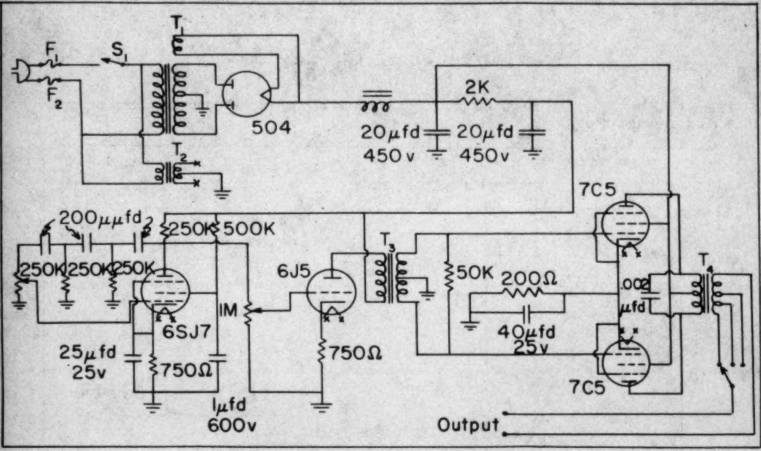

Fig. 2--Audio-frequency generator circuit

The combined potentiometer-bridge circuit is shown in Figure 3. Switching from the potentiometer circuit to the bridge circuit is facilitated by a six-pole, two-throw rotary switch. The instrument also incorporates a circuit for applying a third potential to the model and a control, R_5, for varying the third potential. Input to the instrument is controlled by the variable resistance R_4 and the on-off switch S_3. The components of the instrument are of standard design. All bridge resistors are of the precision wire-wound type with tolerances of one per cent. The potentiometer has a tolerance of 0.5 pct and is driven by a Gibbs-Micro-Dial 746. The pair of head-phones is of the standard high-impedance, magnetic type connected in parallel for closer impedance match. The voltmeter is of the d'Arsonval type with full-wave rectification.

The purpose of the bridge circuit is to measure the total resistance of the model by means of a wheatstone bridge as shown in Figure 3a. The bridge is balanced by selecting the proper resistance range R_3 and adjusting the ten-turn helical potentiometer for minimum tone in the phones. The potential difference across the model being observed from the voltmeter, the current I through the model can be computed.

The function of the potentiometer circuit is to measure the potential difference V between the well-electrode and a point at the top of the conductor at distance r away by balancing the bridge shown in Figure 3b. The potentiometer reading gives the required value of V as a portion of the total potential difference across the model as read from the voltmeter.

To determine the size of the well electrode and the specific conductivity of the salt solution, the well electrode is adjusted to fully penetrate the solution (d/D = 1). The well-known result for fully penetrating wells is then used

$$\frac{\sigma DV}{I} = \frac{KDh}{Q} = \frac{1}{2\pi}\log_e\left(\frac{r}{r_w}\right) \qquad \text{(3)}$$

With V_1 and V_2 denoting the potential differences between the well and points at distances r_1 and r_2 away respectively

$$\frac{\sigma DV_1}{I} = \frac{1}{2\pi}\log_e\left(\frac{r_1}{r_w}\right)$$

and

$$\frac{\sigma DV_2}{I} = \frac{1}{2\pi}\log_e\left(\frac{r_2}{r_w}\right)$$

From these two equations the values of r_w and σ can be computed, the other quantities being observed from the model.

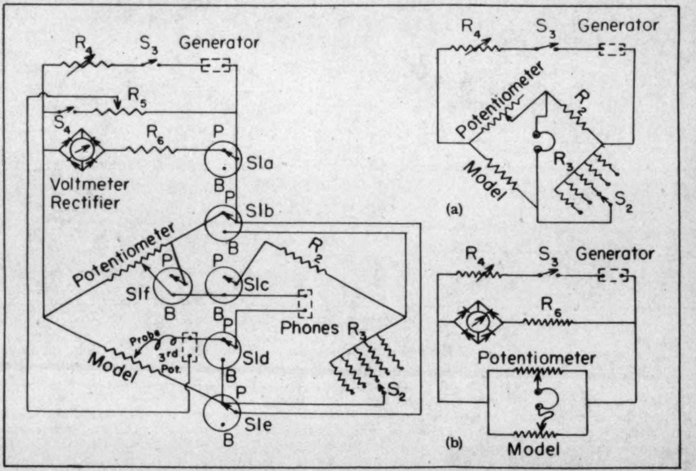
R₄
S₃
Generator
R₅
S₄
R₆
P
Sla
Voltmeter
Rectifier
B
P
Slb
Potentiometer
R₂
B
P
P
Slf
Slc
B
B
Phones
R₃
Probe
3rd Pot.
Model
P
Sld
B
P
S₂
Sle
B
R₄
S₃
Generator
Potentiometer
R₂
Model
R₃
S₂
(a)
R₄
S₃
Generator
R₆
Potentiometer
Model
(b)

Fig. 3--Potentiometer bridge circuit; (a) bridge circuit; (b) potentiometer circuit

Test results--The test results are shown graphically in Figures 4 and 5 on semi-logarithmic scales. It can be seen that, in the region where r/D is greater than 1 - (d/D), all the lines are parallel to the line for full penetration. Thus the value of h for a partially penetrating well may be written as

$$h = h_F + \Delta h = \frac{Q}{2\pi KD}\log_e\left(\frac{r}{r_w}\right) + \Delta h \qquad \text{(4)}$$

where h_F is, for the same discharge, the drawdown that would occur if the aquifer were fully penetrated. In this equation, Δh is the increase of drawdown due to partial penetration. The magnitude of Δh depends on D/r_w, d/D, and r/D. However, for a particular case, Δh is essentially constant for the whole aquifer except where r is less than (D - d). To find this constant magnitude of Δh, the observed values of KDh/Q at r = D are chosen for convenience and plotted in Figure 6. Additional data obtained from MUSKAT [1937, p. 274] are also included in the same figure to extend the

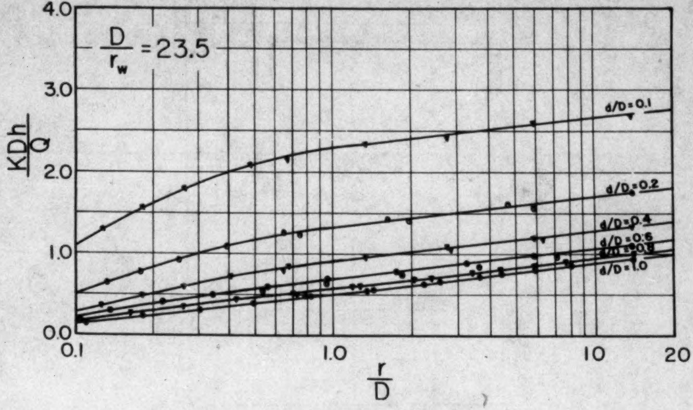

Fig. 4--Experimental data for $D/r_w = 23.5$

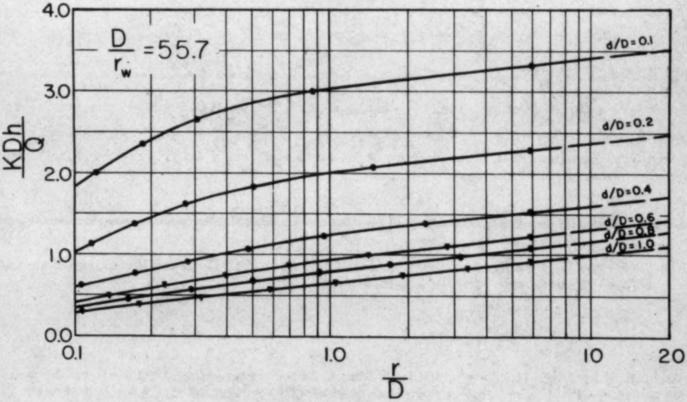

Fig. 5--Experimental data for $D/r_w = 55.7$

range of application of the observed data. From Figure 6, it can be seen that for r = D

$$\frac{KDh}{Q} = \frac{KDh_F}{Q}\left(\frac{D}{d}\right)^n$$

where n depends on D/r_w only. Comparing this expression with (4) with r = D

$$\Delta h = \frac{Q}{2\pi KD}\left[\left(\frac{D}{d}\right)^n - 1\right]\log_e\left(\frac{D}{r_w}\right) \qquad (5)$$

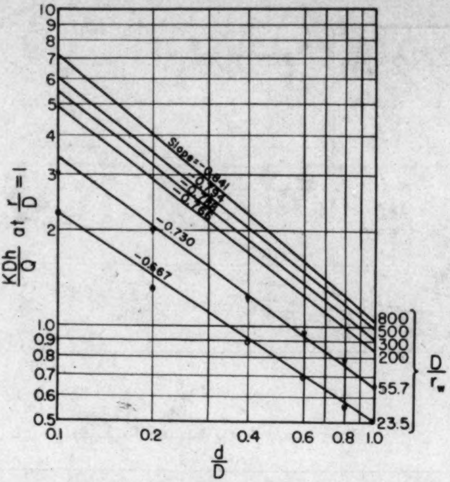

Fig. 6--KDh/Q at r = D

Substituting (5) into (4)

$$\frac{KDh}{Q} = \frac{1}{2\pi}\log_e\left(\frac{r}{r_w}\right) + \frac{1}{2\pi}\left[\left(\frac{D}{d}\right)^n - 1\right]\log_e\left(\frac{D}{r_w}\right) \quad \ldots\ldots\ldots\ldots (6)$$

To evaluate the exponent n, a curve showing the relationship of n to D/r_w is plotted in Figure 7 on log-log scales. From the graph

$$n = \frac{3}{4}\left(\frac{D}{100\,r_w}\right)^{.08} \cong \frac{3}{4} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Eq. (5), (6), and (7) have been obtained under the following conditions and therefore can be used with confidence when these conditions are satisfied

$$800 \geq \frac{D}{r_w} \geq 25 \qquad r \geq D - d \qquad 1 \geq \frac{d}{D} \geq 0.1$$

Note that (6) satisfies (1) as required for radial flow beyond a certain distance from the well. For r larger than (D - d), the value of Δh is independent of r as given by (5). Eq. (2) by Kozeny gives a value of Δh proportional to $\log_e r$.

To show the effect of partial penetration on the drawdown, let h and h_F be the drawdown for partial penetration and full penetration of the same aquifer respectively for the same discharge. According to (4) and (5)

$$\frac{h}{h_F} = 1 + \frac{\Delta h}{h_F} = 1 + \frac{\log D - \log r_w}{\log r - \log r_w}\left[\left(\frac{D}{d}\right)^n - 1\right]$$

This expression is plotted in Figure 8 with a value of 3/4 for n.

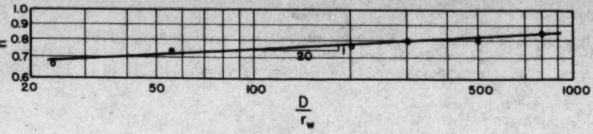

Fig. 7--The value of n in Eq. (2)

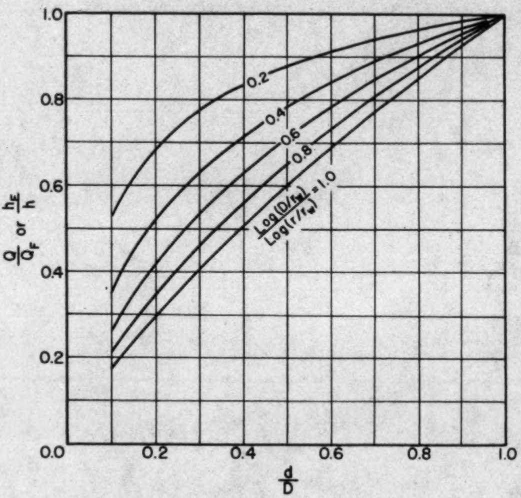

Fig. 8--Effect of partial penetration of an aquifer

To show the effect of partial penetration on the discharge, let Q and Q_F be the discharge for partial penetration and full penetration of the same aquifer respectively for the same drawdown. According to (6)

$$\frac{Q_F}{Q} = 1 + \frac{\log D - \log r_w}{\log r - \log r_w}\left[\left(\frac{D}{d}\right)^n - 1\right]$$

This expression is also represented by Figure 8.

Conclusion--The electrical model used in this investigation has produced data consistent with those by Muskat as shown in Figure 6. Except for a small area around the well where r is less than (D - d), the drawdown of a partially penetrating well differs by a constant amount from that of a well fully penetrating the aquifer. A simple empirical formula has been obtained for the relation between drawdown and yield, as shown in (6). This equation satisfies (1) in that the flow is essentially radial beyond a certain distance from the well. Since the drawdown curve of a partially penetrating well has been found to be geometrically similar to that of a fully penetrating well, except for a small area around the well, the study of many problems of wells, such as the interference of wells, can be made for partially penetrating wells in the same manner as for fully penetrating wells.

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THE APPLICATION OF THE RING INFILTROMETER TO DIAGNOSIS OF IRRIGATION PROBLEMS IN SOUTHERN CALIFORNIA

V. S. Aronovici

Abstract--A study was made of the merits of one-square-foot ring infiltrometers as a diagnostic tool in evaluating furrow irrigation in citrus orchards of Southern California. The results indicate that this device is not suited to quantitative evaluation of irrigation-furrow performance but does provide qualitative values, which have use in the study of diversified soil conditions that influence irrigation-furrow performance.

The forces involved in the movement of water into the soil from furrows include both gravity and suction head. These forces are difficult to evaluate and impossible to duplicate with a conventional ring infiltrometer. Ring infiltrometers, alone, do not provide sufficient information concerning the character of the soil profile to evaluate adequately irrigation problems in citrus orchards.

Introduction--To prevent confusion in terminology in this report, the term 'infiltration rate' refers to the rate of movement of water into the soil from rings, furrows, and sprinkler irrigation. Separation has not been made between partial and complete soil coverage, although there is a recognizable difference.

The use of the ring infiltrometer to evaluate infiltration characteristics of soils is not new. Comparison of infiltration rates as observed by ring infiltrometers with the field performance of irrigation borders is described in unpublished works of James Marr, Office of Public Roads and Rural Engineering, U. S. Department of Agriculture, in 1917. MUNTZ [1908] of France studied rates of water movement into the soil in 1908. Application of the ring infiltrometer to analyses of erosion-control practices and watershed analysis was extensively investigated by FREE and Others [1940] in the 1930's. In recent years, the ring infiltrometer has been widely utilized as a diagnostic tool in irrigation studies of the West.

Objective--It is the purpose of this study to develop methods for evaluation of furrow-irrigation systems in citrus orchards of Southern California, and to establish the relative influence of furrow length, duration and rate of water application, cultural practices, soil profile, and soil-moisture distribution upon these systems. This discussion deals primarily with the evaluation of the reliability of infiltration rates, secured by means of the ring infiltrometer as an index of irrigation-furrow infiltration. Is the infiltration rate measured by the ring infiltrometer the same as in a furrow, or is there some consistent relationship between them? It further endeavors to establish the practicability of using the ring infiltrometer as a part of irrigation-system investigation. To answer these questions, comparisons were made of furrow and ring infiltration rates and coefficients of permeability of soil cores representative of the soil profile.

Problem--The problems encountered in field studies of this nature are numerous. Variations in soil profile within a single irrigation-furrow length may be considerable. Soil-moisture conditions at the time of the irrigation test and differences in soil tilth and structure, even within a span of two citrus trees, complicate measurements of this type. As will be shown below, center furrows perform differently from those adjacent to trees. Furrow width, channel storage, and fluctuations in application rates during a single irrigation are variables that must be considered. Consequently, emphasis has been placed upon a single furrow or a portion of a furrow in comparing the infiltrometer performance with furrow performance.

Procedure--A comparative study of the ring infiltrometer and irrigation-furrow infiltration rates was made on 18 sites representing a variety of cultural practices and soil profiles which present problems in citrus irrigation. The soils are alluvial, derived from sediments of granitic origin, and range from having a slightly developed subsoil to strongly developed clay subsoils on elevated terraces. All but one of the studies were confined to the Hanford, Ramona, and Placentia family of soils. Cultural practices varied but may be classified in one of two broad groups. The first was non-tillage, with oil spray used to control weeds. The second included weed control by means of two or more diskings each year.

The infiltrometer used for these observations consists of a single ring constructed of 16-gage galvanized iron, butt-welded into a ring containing a one-square-foot area. The unit is 12 inches long. During all early studies, a constant depth of 2.5 to 3.0 inches of water was maintained in the rings by means of a Mariotte bottle utilizing a two-liter graduated burette. Minor fluctuations in the water level were checked by means of a hook gage bolted to the side of the ring. It was found that head variations in the magnitude of one or two inches made little or no difference in infiltration rates. This is because the hydraulic gradient produced by the capillary potential gradient between the wetting front and the furrow is a predominant force producing infiltration from the furrow. At the time of irrigation the soil moisture is considerably below field capacity and frequently approaches wilting near the soil surface. Consequently, the Mariotte bottle was discarded and water was maintained in the rings by adding given quantities when needed.

Each ring is driven into the soil by placing a 3/4-inch thick steel plate over it, upon which the operator stands while he tamps the ring into place with a regulation soil-tube hammer. The combination of the operator's weight and the sharp pounding with the hammer makes it possible to drive the rings evenly and easily into place. In this study, the rings were driven three inches below average level of the soil surface.

Ring infiltrometers were placed either directly in or adjacent to the irrigation furrows studied. In some tests, irrigation water in the furrow was by-passed around the rings by means of pipes. Infiltration from irrigation furrows was accurately measured by recording both inflow and outflow. Both the 90° V-notch weir and simple bucketing were used in the measurement of water flow at the upper end, center, and lower end of the furrow. Infiltration rates were determined by subtracting outflow from inflow and dividing the result by the wetted area in the furrow.

Soil cores, two inches or three inches in diameter and three inches long, were secured several days after the infiltration runs by means of the Uhland or Pomona type [DONNAN, 1952] coring device. Soil-core permeability coefficients in inches per square inch per hour per unit hydraulic gradient were determined in the laboratory.

All infiltration rates comparing the ring infiltrometer rates with furrow-infiltration rates were reduced to values of cubic inches per square inch per hour. Wetted surface areas were used in preference to lineal values in computing furrow-infiltration rates.

Field tests described in this paper are representative of the variety of conditions encountered. All studies were conducted under normal irrigation conditions prevailing in the areas. At frequent intervals throughout the irrigation runs, average wetted surface area and capillary spread from the furrows were measured. Soil-moisture samples were taken preceding and following the irrigation.

Results--The first sample, presented in Figure 1, compares the furrow-infiltration rate with the rates of ring infiltrometers placed within the tree-row furrow and in the tree row several feet from the furrow. The orchard was clean cultivated on a deep terrace soil (Ramona). The surface soil is sandy loam with a moderately developed clay loam subsoil at 15 inches. Pre-irrigation soil moisture was at half the total available moisture level. No strong plowsole development was observed.

The second example, presented in Figure 2, compares two furrow-infiltration rates with the ring-infiltrometer and soil-core permeability on a terrace soil similar to that of the first study. One furrow was in clean-cultivated land; the other was in land where an oil spray was used instead of cultivation. These two furrows were three tree rows (66 ft) apart. Soil differences at this location were found to be slightly below ground surface. The difference in furrow performance under the two cultural practices was marked. The ring infiltrometer, however, did not indicate this difference. Pre-irrigation moisture was, at both stations, approximately at one-third of total available soil moisture in the first two feet of soil.

The third example, presented in Figure 3, compares a group of four furrow-infiltration rates with those of ring infiltrometers placed in each furrow. In this study, the surface soil was silt loam in texture and the subsoil was clay loam with considerably reduced permeability at the 24-inch depth. Less than a third of the available soil moisture was depleted in the upper two feet of profile at the time of irrigation. Soil cores, ring infiltrometers, and furrows showed less divergence than in the previous tests. Surface soil compaction in the furrows is indicated by comparing the soil-core permeability taken in the tree row with those obtained in the furrows (Fig. 3). Volume weight of the surface three inches of soil in the furrows was 1.54 compared with 1.47 in the tree row. Subsurface differences are not so marked.

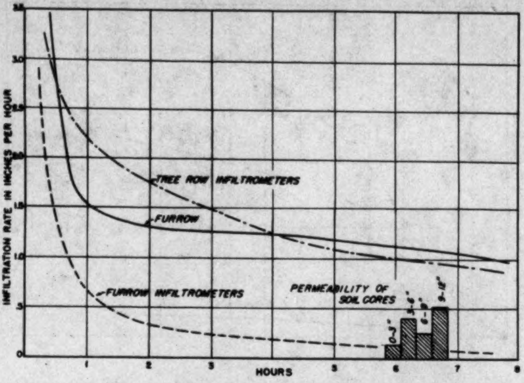

Fig. 1--Comparison of furrow-infiltration rate with ring infiltrometers and soil-core permeability

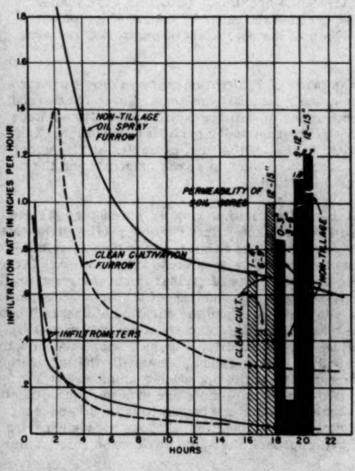

Fig. 2--Comparison of two furrow-infiltration rates with ring infiltrometers and soil-core permeability on similar soil with different culture practices

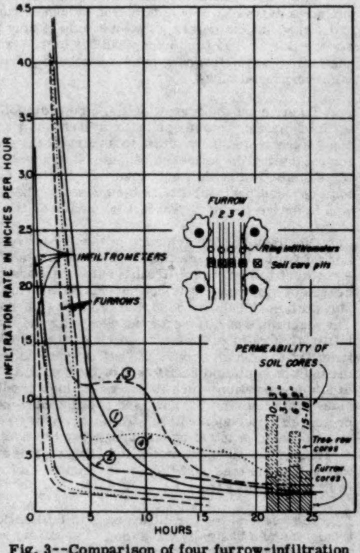

Fig. 3--Comparison of four furrow-infiltration rates with ring infiltrometers and soil-core permeability with high initial soil moisture in profile

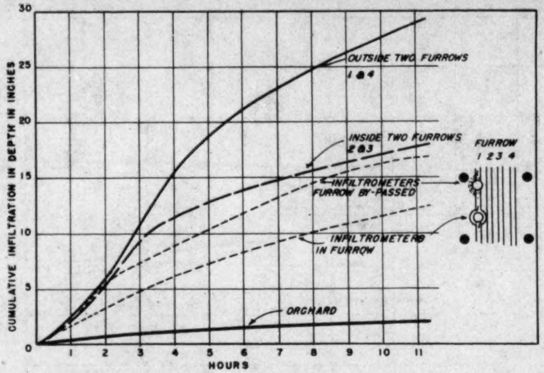

Fig. 4--Comparison of cumulative infiltration from furrows with ring infiltrometers

The fourth example, illustrated in Figure 4, also located on a terrace soil, compares the cumulative depth of water application by center furrows and tree-row furrows with the infiltration from ring infiltrometers. Two methods of ring placement were used. Both sets were placed in furrow No. 1. The first group had the furrow water by-pass the rings by means of a pipe while the furrow water flowed around the second group. This is the equivalent of comparing buffered with unbuffered rings.

To augment the furrow study, a comparison was made of infiltration rates in citrus orchards, utilizing an under-tree sprinkler system, soil cores, and ring infiltrometers. Three cover conditions were tested in an effort to ascertain the effectiveness of soil cores and ring infiltrometers for evaluating the influence of cultural practices on infiltration under sprinkler irrigation. The plots studied were on sandy loam terrace soil similar to that of the first example, with considerably reduced permeability in the subsoil. The first two plots were in citrus orchards and the third was in native pasture. Table 1 summarizes the results obtained.

Discussion--The evidence presented above indicates that neither ring infiltrometers, as used, nor coefficient of permeability measurements of soil cores taken within the soil profile gives rates equivalent to furrow-infiltration rates, nor are the results of these observations comparable in degree of variance. It is not surprising that the coefficients of permeability do not compare favorably with permeability observed in furrows because the conditions of measurement were not similar. The magnitude of difference between ring and furrow was greater than expected. The ratios between infiltration rates of furrows and rings change with site conditions and the duration of observations from 1:1 to as high as 9:1. It is of interest to note that infiltration rates from center furrows approach the minimum coefficient of permeability values for the profile. Figure 3 shows an exception to this observation which is due to the high pre-irrigation soil moisture. Generally the infiltration rates from the ring, furrow, and coefficient of permeability tend to approach a common level with prolonged water application. This will most likely occur when soil moisture exceeds field capacity and moisture penetration has progressed to some depth, or moisture begins to build up above a stratum of very low permeability. Figure 3 demonstrates this condition. It does not necessarily follow that the tree-row furrow and center furrow will approach the same infiltration rate. This is illustrated in Figure 4.

The reasons for the differences in infiltration rates from the several furrows and ring infiltrometers are basically the same. Two forces enter into the movement of water into the soil. The first is gravity, or pressure head. It is dependent upon the depth of water and relative surface area at ground surface. This may be the same for all furrows and for the ring infiltrometer. If this were the only force involved in the movement of water into the soil profile, it would probably be a relatively simple matter to adjust coefficient of permeability and ring values to field conditions. The second force is suction head, produced by the capillary potential gradient between the wetting

Table 1--Relation between infiltration rates observed by ring infiltrometers, soil cores, and sprinkler irrigation

Type of measurement	Cover conditions		
	Citrus clean cultivated	Citrus non-tillage oil spray	Native pasture
	in/hr	in/hr	in/hr
Sprinkler system			
End 100 minutes	0.3	0.3	> 0.3
End 300 minutes	0.3[a]	0.3[b]	> 0.6[c]
Ring infiltrometer with 36-inch buffer pond			
End 100 minutes	0.4	0.4	3.4
End 300 minutes	0.2	0.2	1.2
Ring infiltrometer without 36-inch buffer pond			
End 100 minutes	0.8	0.4	1.9
End 300 minutes	0.5	0.4	2.0
Soil cores - coefficients of permeability			
0-3 inch depth	1.4	1.8	2.2
3-6 inch depth	0.4	1.0	1.0
6-9 inch depth	0.3	0.8	1.8

[a] Measurable runoff began at 300 minutes with application rate slightly above 0.26 inch per hour.

[b] Measurable runoff began between 300 and 400 minutes with application rate at 0.31 inch per hour.

[c] Field infiltration rate from sprinklers was not measurable because maximum possible application rate did not exceed infiltration rate.

front and dry or non-irrigated soil [RICHARDS, 1931]. The magnitude of the suction head at any time during infiltration from a furrow is dependent upon four conditions: (1) the difference in soil moisture at the interface, (2) the size of the interface as related to the surface wetted area, (3) the distance from the wetted area to the interface, and (4) the relative capillary conductivity of the soil between the surface and the wetting front.

To a large extent, these four factors are a major cause for the characteristic exponential curve produced by plotting infiltration rates with time. Any field condition which may contribute to the increase or reduction of the net suction head will result in an increase or reduction in the observed infiltration rates. Furrow silting, erosion, soil-particle rearrangement, and deterioration of soil structure are contributory. They can not be major factors as evidenced by the fact that ring-infiltrometer infiltration rates are initially and continue to remain consistently lower than furrow rates. Yet, the portion of furrow contained within the ring is not subject to silting, erosion, or particle rearrangement due to water flow over the surface. Figure 5 (A, B, and C) illustrates the pattern of flow from the ring infiltrometer, center-row, and tree-row, irrigation furrows. The wetting front progresses normal to lines of flow. It is evident by these examples that a considerable reduction of the wetting front area of the center furrow is caused by the influence of water moving out from furrows on either side. The tree-row furrow has a considerably larger area in which the wetting front is not affected. The relationship between the wetted area above the plowsole for A, B, and C, compared with the wetted surface area, is approximately 1:1, 2:1, and 3:1, respectively. This ratio does not differ greatly from those of some of the actual field observations of lateral percolation observed by means of trenching and soil-moisture sampling subsequent to irrigation. Figure 5 (B, C) illustrates the relatively even distribution of soil moisture gained as a result of irrigation. Table 2 summarizes three observations of soil-moisture gain following irrigation.

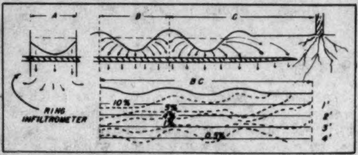

Fig. 5--Irrigation water flow pattern from: (A) ring infiltrometer, (B) center furrow, (C) tree furrow, (BC) soil-moisture gain

Table 2--Summary of moisture sampling of three plots showing soil-moisture gain following irrigation with three furrows

Tree row	18 inches from right furrow	Right furrow	Ridge	Center furrow	Ridge	Left furrow	18 inches from left furrow	Tree row
Soil-moisture gain in inches of water for four-foot soil depth								
0.94	1.04	3.48	1.03	0.24	2.50	3.19	4.42	. . .[a]
0.66	0.50	2.03	2.85	1.00	1.30	0.48	2.30	0.50[b]
0.97	0.72	0.98	0.85	2.20	1.00	1.54	0.20	0.65[c]

[a] Only moderately developed plowsole.
[b] Strongly developed plowsole.
[c] Entire profile with low permeability.

There is substantial evidence to indicate that under conditions of reduced permeability either on the furrow bottom, plowsole, or soil stratum near the surface, the conditions illustrated in Figure 5 occur. Often this results in a more even distribution of soil moisture in the orchard than would occur under conditions of very permeable soil. Furrow width or total wetted surface area appears to have no direct bearing upon the infiltration rate from a furrow on a wetted area basis. This is because the lateral flow of water from the furrow is more dependent upon the water contact with furrow sides and capillary flow laterally. The width of the furrow has little influence upon this movement. Lateral flow of water from furrows presents a major reason for poor correlation between a ring infiltrometer and the furrow. The ring infiltrometer, when driven into the furrow three to six inches, prevents lateral flow above that depth. This is clearly demonstrated when comparing two orchards located on similar soil. The first was irrigated by means of two broad furrows and the second by three narrow furrows. In the first case the average wetted surface area for the two furrows was 302 sq ft per tree row and the second was 187 sq ft. The surface area of capillary spread observed at ground surface was 560 sq ft for the broad furrows and 634 sq ft for the narrow furrows. These are ratios of 1.9:1 and 3.4:1, respectively. The net infiltration rate was 0.039 inch per hour for the wide furrows and 0.088 inch per hour for the narrow furrows.

To illustrate the significant differences in furrow infiltration rates as related to the evaluation of irrigation practices, Table 3 summarizes the water balance for an irrigation. Note that the center furrows produced about one-fourth of the total infiltration.

Table 3--Furrow-irrigation analysis for clean cultivated citrus orchard on loam terrace soil having moderately reduced permeability in subsoil

Value	Furrow number				Total
	1	2	3	4	
	cu ft	cu ft	cu ft	cu ft	cu ft
Total cubic feet delivered to furrow	409.7	242.7	227.8	430.2	1310.4
Runoff at half-way point of furrow	189.9	192.0	133.9	213.4	729.2
Net infiltration	219.8	50.7	93.9	216.8	581.2
Runoff at lower end of furrow	57.9	78.3	78.5	66.9	281.6
Net infiltration lower half furrow	132.0	113.7	55.4	146.5	447.6
Net infiltration entire furrow	351.8	164.4	149.3	363.3	1028.8
Furrow efficiency in per cent	85.6	67.7	65.5	84.4	78.5[a]

[a] There was no loss to deep percolation as indicated by soil-moisture sampling.

From the preceding data it becomes quite apparent that a conventional infiltrometer which does not record surface lateral capillary flow does not reflect the performance of an irrigation furrow. Where irrigation practices involve wetting of the entire soil surface by sprinklers, furrow corrugation, or border checks, then the ratio between wetting surface and the wetting front will be similar for a buffered ring and the field. Studies by the author and other workers [CRIDDLE, 1951] have found fairly good correlation under these conditions.

Comparing the results obtained by the ring infiltrometer, soil-core coefficient of permeability, and the performance of furrows, it is apparent that the ring infiltrometer does not materially aid in characterizing individual segments of the soil profile as related to reduced permeability. Observed infiltration rates are a product of several variables such as depth to zones of reduced permeability, initial soil moisture, and depth of ring in the soil. Soil-core coefficient of permeability, on the other hand, does provide an excellent tool for establishing zones of reduced permeability, and assists materially in establishing a cause for good or poor irrigation-water penetration and distribution. If water moved into the soil from a furrow under nearly saturated conditions and the suction head was small, it might be possible to estimate furrow-infiltration rates. During a large portion of the irrigation time, neither is the soil saturated nor is the suction head known. Consequently, the core-permeability values cannot be used directly.

When the soil is thoroughly wetted and the suction head is no longer a significant factor, there is a decided narrowing of the gaps among infiltration measurements with the ring, furrow, and core. Unfortunately, this has little value because the decline in infiltration rate with time is as significant as the rates themselves in the evaluation of irrigation systems. Commonly, more than one-half of the total irrigation-water infiltration from furrows takes place in the first third or fourth of the total irrigation time.

If it were possible to design an infiltrometer which could simulate the same relationships of wetting surface area to wetting front, layers of restricted permeability, and movement of water from the furrow into the soil, it might be possible to make reliable evaluations of furrow performances. Fred Hamilton, in an unpublished report, describes a furrow infiltrometer that consists of two parallel galvanized sheet-metal plates 30 by 12 inches held exactly one foot apart by steel braces. An infiltrometer of this type placed in a furrow normal to direction of flow might satisfy these requirements. The plates are driven into the furrow bottom approximately two inches and five to six inches in the furrow sides. If used during an irrigation, water is by-passed around the infiltrometer by means of two-inch flexible hose. Infiltration rates are measured on the basis of cubic feet of water per lineal foot of furrow per hour in contrast to the conventional inches per square inch of wetted surface per hour. The term 'furrow absorption efficiency' is suggested for this value. Table 4 briefly summarizes four furrow infiltrometer tests.

Table 4--Comparison of furrow absorption efficiency of furrows with Fred Hamilton type infiltrometer

Elapsed time	Test 1		Test 2		Test 3		Test 4	
	Furrow	Infiltrometer	Furrow	Infiltrometer	Furrow	Infiltrometer	Furrow	Infiltrometer
	Infiltration in cubic feet per lineal foot per hour							
4	0.085	0.137	0.085	0.036	0.197	0.069	0.125	0.068
10	0.021	0.102	0.063	0.031	0.119	0.048	0.058	0.062
20	0.014	0.043	0.053	0.015	0.123	0.076	0.046	0.045
32	0.011	0.025	0.035	0.017	0.085	0.041	0.033	0.029

These results indicate more favorable correlation with furrows than the ring infiltrometer. However, they are still far from reliable. Reasons for such variations may be the difficulty in selecting representative sites on a furrow. The observation illustrated shows furrow infiltrometer values both higher and lower than the furrow infiltration rates, suggesting that this may be a major reason for lack of good correlation. Additional field trials are needed before conclusive data are presented.

Conclusion--The analysis of a series of furrow-irrigation systems in citrus orchards has suggested the following conclusions:

(1) The conventional ring infiltrometer containing one square foot of surface area, placed in an irrigation furrow in the several ways described, and observed during irrigation is not indicative of the furrow infiltration rate.

(2) The ring infiltrometer has value as a qualitative measurement of a site condition as indicated by the results presented. It is not capable of establishing reliable quantitative values of furrow performance under the conditions studied. Further, it is not possible to read into the results obtained by the infiltrometer the character of the soil profile as related to a zone of low and high permeability.

(3) The soil-core coefficients of permeability are reasonably accurate means of evaluating the soil profile but the data are not directly applicable to the diagnosis of irrigation-furrow performance.

(4) It is apparent that the suction head produced by the capillary potential gradient at the wetting front strongly influences the rate at which water enters the soil from the furrow. This force is influenced by moisture content, profile, pore-size distribution, capillary conductivity of the soil, and nature of the wetting front.

(5) Furrow width or wetted surface area has small influence on lateral capillary flow.

(6) When more than two irrigation furrows are used between tree rows, considerable difference in individual furrow performance is found. Usually the center furrows have slower infiltration rates than the tree furrows.

(7) The Hamilton furrow infiltrometer appears to have promise for the evaluation of furrow-infiltration capacities.

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DIRECTION STUDIES USING MICROSEISM GROUND-PARTICLE MOTION

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Abstract--Ground-particle trajectories were constructed for Palisades microseisms originating in storms having various positions and azimuths with respect to the continental margin. It was found that good directional success was obtained for sources on the continental shelf or for deep-water storms on an azimuth normal to the continental margin. The complete lack of directional relationship between particle motion and source direction for deep-water sources having azimuths oblique to the coast is ascribed to simple refraction or interference between waves having multiple refraction paths. Microseisms arriving at Palisades with eight- to nine-second period and one- to two-micron ground amplitude have been traced back to North Pacific sources more than 5000 km away. Very good directional correlation was obtained in these cases between ground-particle motion and source direction. The results of the study appear to explain the original tripartite success of Ramirez in obtaining good locations for Atlantic storms.

Introduction--Determinations of the directions of microseism-generating sources by means of tripartite and Rayleigh-wave techniques [DONN and BLAIK, 1953; BLAIK and DONN, in press; KAMMER and DINGER, 1951; IKEGAMI, 1951] have generally proven inadequate. The sources studied in the past were tropical or extra-tropical cyclones over deep water beyond the edge of the shelf. It was concluded [DONN and BLAIK, 1953; BLAIK and DONN, in press] that refraction at the continental margin, in addition to the presence of broad or multiple source areas, were the main causes of failure not inherent in the procedure. It was argued from this that better correlation with direction should be obtained using microseisms from limited generating areas on the continental shelf, where the effect of the margin is eliminated, and from distant storms whose azimuths from the station are fairly normal to the coast.

Since Rayleigh-wave motion was demonstrated for Palisades microseisms [BLAIK and DONN, in press], it was concluded that the above ideas could be checked by determining ground-particle motion from matched three-component seismographs, and by noting in particular the projection of this motion in the horizontal plane. For most of the cases the Palisades Benioff Seismographs ($T_o = 1$, $T_g = 75$) were used. In two cases the Palisades Columbia instrument ($T_o = 12$, $T_g = 15$) were used, owing to their higher magnification. The appropriate instruments are designated in each case.

The theoretical errors involved in the procedure of azimuth determinations from horizontal trajectories originates in instrumental and reading errors. The former depends on variations from expected phase response, magnifications and drum speeds. Reading errors result from inaccuracies in time and amplitude measurements on the records and from estimations of the exact elongation directions of the orbits. The reading errors can be evaluated more definitely than those of instrumental origin. It is estimated that the maximum theoretical error, if the causes are cumulative, could be from 50 to 75°. However, the consistency of the results to be given below indicates that operation was well within the theoretical error as a result of the great care taken and compensating effects.

Microseisms from continental shelf sources--Figures 1 and 2 show two different cold fronts extending in a northeast-southwest direction over local shelf waters. As a result of the frontal alignment and the coastal configuration in the vicinity of Palisades (P), the area of microseism generation between the cold fronts and the coast is quite restricted in size and is limited to a sector between south and southeast of Palisades.

Thirty microseism groups, which were particularly coherent and prominent on the vertical records and which were readily identified on the horizontals, were selected for measurement from the microseism storm corresponding to conditions shown in Figure 1. These were short-period microseisms (three seconds) and were completely typical of all frontal microseisms recorded and studied at this station. Phase relations among the three components were proper for Rayleigh-wave motion. Horizontal ground-particle trajectories were constructed from the Benioff seismograms for the maximum wave from each of the 30 groups. This motion is reproduced in Figure 3.

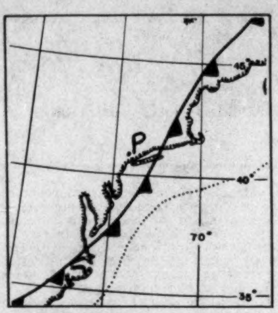


Fig. 1--Map of cold front, October 28, 1952, 18h 30m GMT

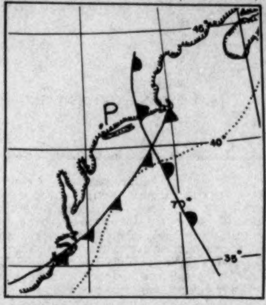


Fig. 2--Map of cold front, May 7, 1952, 06h 30m GMT

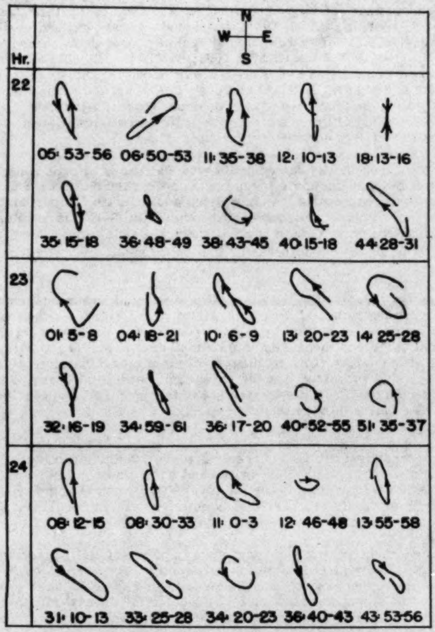


Fig. 3--Horizontal trajectories from Palisades Benioff seismograph for October 28-29, 1952

Most of the orbits show pronounced elongation and are aligned SSE-NNW. A comparison of phases between the vertical and horizontals indicates that all motion was from the SSE. Hence all but the second of the orbits point directly into the frontal or post-frontal zone. In cases where there is departure from good elongation, a recheck of the records showed that the waves in these cases were not as coherent on the horizontals as the visual inspection, on which selection was based, seemed to indicate. The more coherent the wave, the better is the approach to linearity for the horizontal orbit. The mean azimuth of the trajectories is 157°, with a standard deviation of 15°. This error is expected in view of the errors considered above and the broad sector of approach owing to the proximity of even this small generating area.

A second case of typical frontal microseisms was studied for the cold front shown in Figure 2. The selection of microseisms was similar to the above case except that every wave in each of nine good groups was measured, giving a total of 50 waves. The horizontal trajectories (from the Benioff seismographs) are shown in Figure 4, where the orbits from each wave are separated for ease of study. Good elongation is again shown with little scatter from a SSE-NNW direction. All waves arrived from the SSE. The mean azimuth for this set is 166° with a standard deviation of ten degrees. The smaller deviation in this case is probably a result of the greater microseism amplitudes which permitted measurement with greater accuracy.

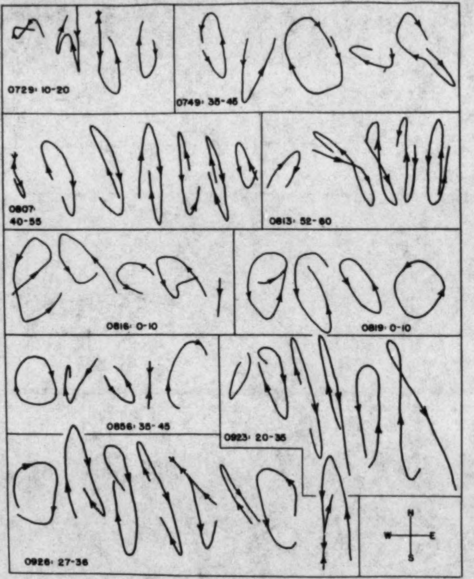


Fig. 4--Horizontal trajectories for May 7, 1952

Again, the waves whose orbits are irregular or exhibit poor elongation show poor coherence when examined carefully. It is a simple matter to select the orbits which may be expected to give the most reliable direction determinations.

Microseisms from distant Atlantic storms--Figure 5 shows a large, intense cyclone extending from the coast to deep water. A very intense microseism storm was recorded at Palisades at this time. Again, on the basis of visual coherence a single wave from each of the 28 good groups was

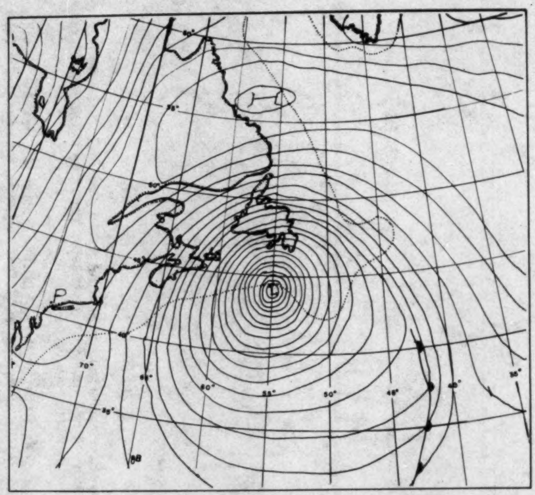
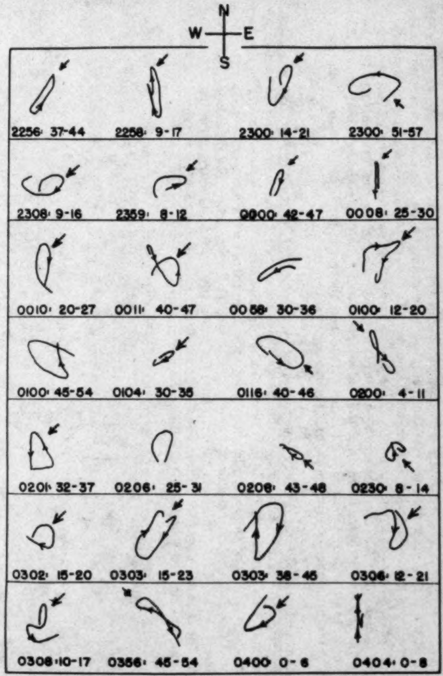


Fig. 5--Large, intense cyclone, November 19, 1952, 06h 30m GMT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2258: 9-17
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2300: 51-57
2308: 9-16
2359: 8-12
0000: 42-47
0008: 25-30
0010: 20-27
0011: 40-47
0058: 30-36
0100: 12-20
0100: 45-54
0104: 30-36
0116: 40-46
0200: 4-11
0201: 32-37
0206: 25-31
0208: 43-48
0230: 8-14
0302: 15-20
0303: 15-23
0303: 38-46
0306: 12-21
0308: 10-17
0356: 45-54
0400: 0-6
0404: 0-8

Fig. 6--Trajectories for November 18-19, 1952 selected for measurement from the Benioff records. Although the dominant microseism groups consisted of waves with about eight-second period, the record was irregular owing to the presence of lower-amplitude, shorter-period microseisms. The association of broad period spectra with storms having considerable variation in depth has already been demonstrated in detail [DONN, 1952]. It is emphasized here that only the dominant microseisms were utilized in construction of trajectories.

The trajectories for the 28 waves selected are shown in Figure 6. Although they have a definite tendency toward elongation, the ellipses are much distorted, and show considerable scatter in their alignment directions. The approach azimuths determined by comparison of vertical with horizontals are indicated by the short arrows external to the orbits. In some cases no directions could be determined. A considerable diversity in travel direction is indicated, with no approach from the east, the direction of the cyclone. If the long-period microseisms originated in the region of the steep pressure gradient around the cyclone center, or nearly due east of Palisades, those traveling toward the station would have entered the continent at a very high angle of incidence, thereby suffering considerable scatter and refraction. There is also the possibility that waves traveling multiple refraction paths would arrive at the station simultaneously. These propagation factors could explain the diversity in azimuths given by the horizontal orbits.

Figure 7 illustrates another strong cyclone nearly due east of Palisades. Figure 8 reproduces the horizontal trajectories from seven good wave groups on the Benioff records. Although many of the orbits show good elongation in the horizontal plane, none of them shows any alignment in the direction of the storm azimuth. The quadrants of approach are indicated by the arrows at the end of each group. The data from these two storms are quite typical of those obtained from cyclones in this position. The lack of any indication of approach from the storm together with the great diversity in direction is certainly of significance in considering microseism propagation.

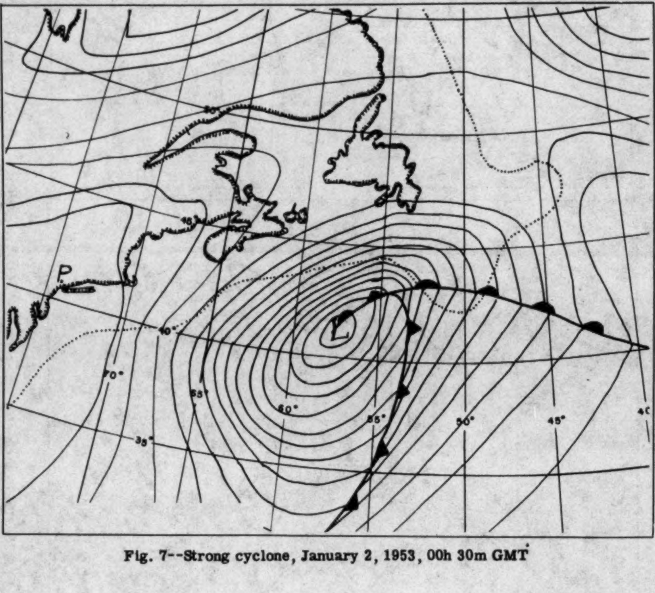

Fig. 7--Strong cyclone, January 2, 1953, 00h 30m GMT

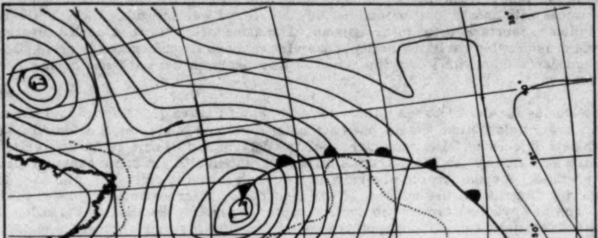
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Fig. 9--Cyclone of November 12, 1952, 00h 30m GMT

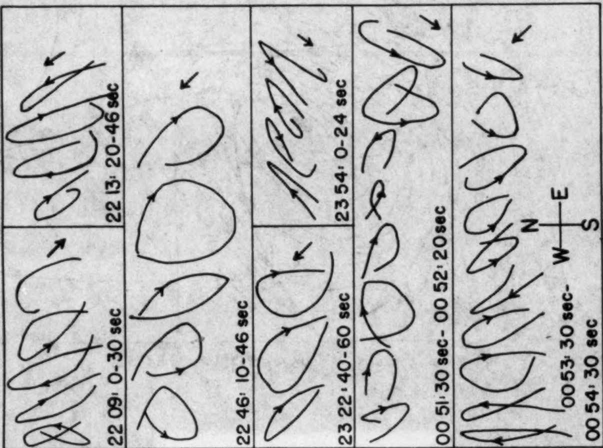

Fig. 8--Trajectories for January 1-2, 1953

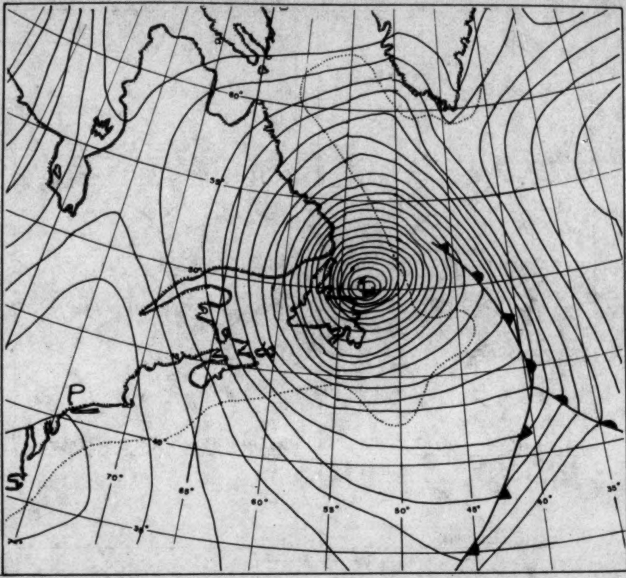

Fig. 10--Cyclone of November 13, 1952, 18h 30m GMT

Figures 9 and 10 show two cyclones centered northeast of Newfoundland and situated on an azimuth from Palisades that is essentially normal to the coast. Figures 11 and 12 show respectively the horizontal trajectories for the microseisms associated with each of these cyclones. The orbits represent continuous waves in the groups illustrated and were constructed from the Benioff records. The average period from both cases was from five to seven seconds. Most of the orbits in both cases show good elongation. Badly distorted ellipses can again be traced to waves that show definite departure from coherent sinusoidal form. All the waves in each case were determined to approach from the northeast quadrant. There is also considerably greater uniformity in the orientation directions shown here, than was exhibited by the two previous cases.

The azimuth of the cyclone center in Figure 9 is 44°. The mean azimuth determined from the orbits showing good elongation in Figure 11 is 42° with a standard deviation of 19°. Since the microseism source region is assumed to be not the center but the region of steep pressure gradient surrounding the center, the sector subtended at Palisades by the generating area would lie within and actually be about equal to the standard deviation sector.

The mean azimuth for the cyclone center shown in Figure 10 is 34°. The mean azimuth determined from the orbits showing good horizontal elongation is 38° with a standard deviation of 17°. The intense part of the cyclone area assumed to be the source region again subtends a sector at Palisades that about equals the standard deviation sector. The difference in direction correlations between these and the preceding two cases seems to arise from the differences in storm positions relative to the continental margin.

Microseisms from distant Pacific storms--Palisades occasionally experiences long-period microseisms (eight to ten seconds) characteristically different from those commonly associated with the frequent intense cyclones in the North Atlantic. These different microseisms arrive in

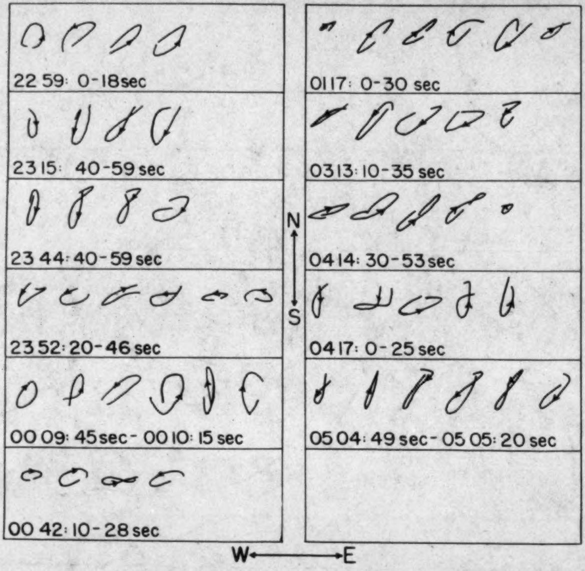

Fig. 11--Trajectories for November 11-12, 1952

long groups often of several minutes duration, the waves of which show almost constant amplitude compared to the typical growth and decay pattern shown by the more common groups from Atlantic sources. There is a complete absence of short-period microseisms, and usually pronounced quiet intervals between groups. Direction studies were made for two such cases and indicated sources in the northeast Pacific Ocean. Ground amplitudes for these two microseism storms were from one to two microns at Palisades.

The Palisades Columbia instruments were used for this purpose since their higher magnification permitted better measurement than did the Benioff. To verify the theoretical calibration of these instruments for the periods being studied, Rayleigh waves R_g [PRESS and EWING, 1952] from the Alaskan shock of May 25, 1950 (azimuth = 327°, Δ = 5369km), were studied and horizontal trajectories constructed. The periods of 9 to 12 seconds were very close to those of the microseisms under consideration. Horizontal trajectories for these earthquake waves are reproduced in Figure 13. The mean azimuth of this group is 337° which gives good success for the location of the epicenter considering the admissible error in procedure.

Horizontal trajectories from the prominent long-period microseism storm of March 29-30, 1953, are shown in Figure 14. Most of the orbits show very good elongation and fairly consistent alignment directions. The mean azimuth of all of the orbits is 322°, with a standard deviation of 17°. The North America weather chart in Figure 15 shows an intense cyclone south of Alaska which has a center azimuth of 319° from Palisades. The standard deviation for the computed azimuth can be reduced by selecting only the most nearly linear orbits in Figure 14. The distorted or rather circular orbits in Figure 14 can conceivably result from interference between the Alaskan storm microseisms with those from some other direction, in this case possibly the region of the steep pressure gradient north of Canada. Similar effects have been observed at Tokyo [IKEGAMI and KISHINOUYE, 1951] where there are often steep pressure gradients at many azimuths.

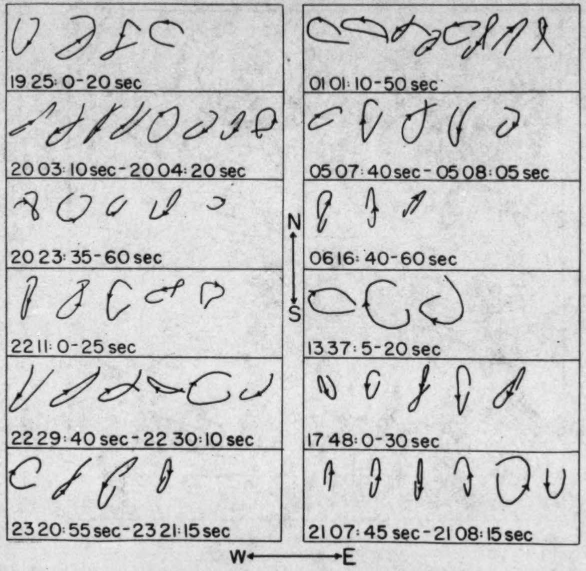
19 25: 0-20 sec
20 03: 10 sec - 20 04: 20 sec
20 23: 35-60 sec
22 11: 0-25 sec
22 29: 40 sec - 22 30: 10 sec
23 20: 55 sec - 23 21: 15 sec
01 01: 10-50 sec
05 07: 40 sec - 05 08: 05 sec
06 16: 40-60 sec
13 37: 5-20 sec
17 48: 0-30 sec
21 07: 45 sec - 21 08: 15 sec
N
S
W
E

Fig. 12--Trajectories for November 13-14, 1952

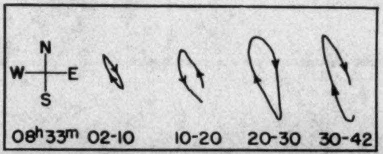
N
W
E
S
08h33m 02-10
10-20
20-30
30-42

Fig. 13--Horizontal trajectories from Palisades Columbia Seismograph for R_g from shock of May 25, 1950

Trajectories were also constructed from the records of the U. S. Coast and Geodetic Survey seismograph in Chicago. These gave a mean azimuth of 334°. The difference between this and the Palisades determinations is certainly in the right direction since Chicago is about 800 mi west of the former station. In addition these microseisms have been clearly identified on the records of Sitka, Denver, Cincinnati, and Cleveland, the identity being based on simultaneity of events and microseism period, the latter varying by no more than one second at the six stations.

Figure 16 shows the trajectories for the long-period microseism storm of January 31 to February 1, 1953. Again the trajectories show marked elongation and fairly constant orientation. These orbits have an average azimuth of 322° with a standard deviation of 14°. Weather maps for this time show an intense cyclonic area with steep pressure gradients extending from the Aleutian Islands southeastward to the Canada-United States border.

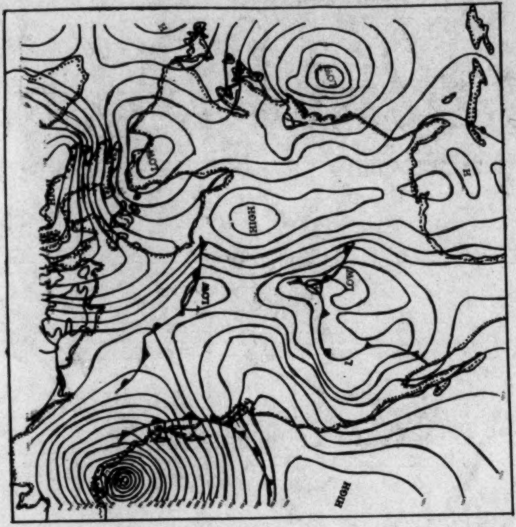
LOW
LOW
HIGH
H
LOW
LOW
LOW
L
HIGH

Fig. 15--Intense cyclone south of Alaska, March 29, 1953, 18h 30m GMT

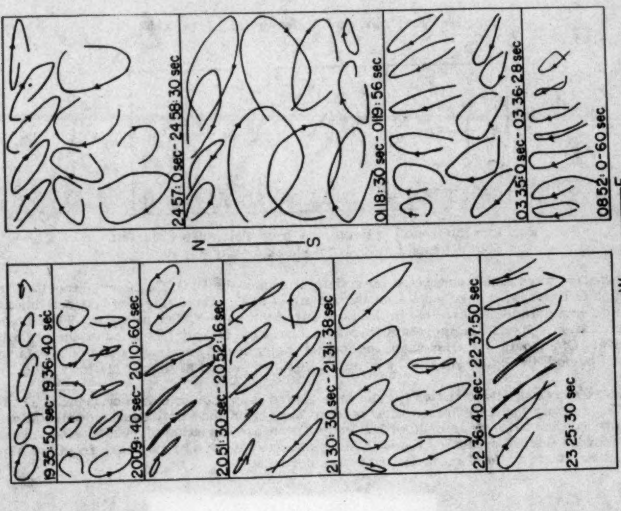

Fig. 14--Trajectories for March 29-30, 1953

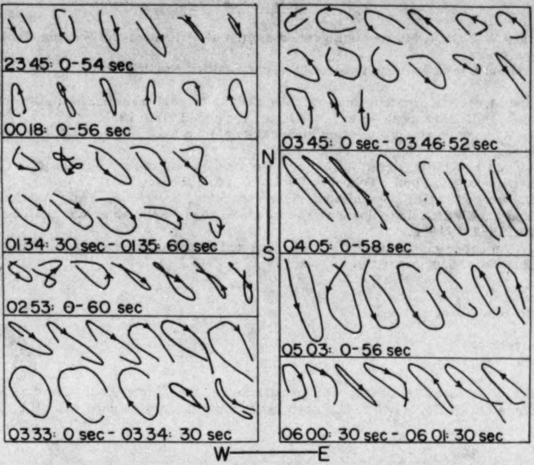

Fig. 16--Trajectories for January 31 to February 1, 1953

Conclusions--Good directional correlation exists between microseism approach direction as determined from ground-particle motions, and direction of the source when the source is either on the continental shelf or on an azimuth normal to the continental margin. When the source is in deep water and on an azimuth oblique to the coast there seems to be no correlation between particle motion and source direction. This is interpreted as a consequence of either simple refraction at the continental edge or a combination of refraction and interference between waves having multiple refraction paths.

It seems most significant that microseisms propagate across more than 5000 km of continent with relatively small attenuation and that good directional correlation exists after long continental propagation between ground-particle motion and cyclone direction. A relationship is suggested between these microseisms and the short-period surface waves (R_g) which appear to have propagation characteristics of refraction and continental preference similar to those of microseisms.

It seems evident from this study that tripartite procedures can only be successful under certain conditions and could not be generally applicable even assuming that all other defects in the procedure were eliminated.

RAMIREZ' [1940] success in obtaining good tripartite directions on Atlantic storms appears explainable by this study. At least half of the hurricane he tracked moved northward on the continental shelf. Further, other larger cyclonic areas he located were either on the shelf or on an azimuth fairly normal to the coast, and some were in the same positions as those for which good locations were obtained in this study. The effects of long continental paths may also have been of importance in minimizing refraction problems.

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EARTHQUAKE INTENSITY ANOMALIES AND MAGMA CHAMBERS OF AZOREAN VOLCANOES

Frederico Machado

Abstract--A procedure for finding a theoretical earthquake intensity is proposed, and the anomaly is defined as the difference between observed and theoretical intensities. Interpretation of the anomalies is discussed. Application of the method to an Azorean earthquake shows conspicuous negative anomalies, which appear to indicate the probable emplacement of magma chambers of the volcanic system formed by Fayal and Pico Islands.

Introduction--In a homogeneous isotropic crust, with a seismic focus reduced to a point, isoseismal lines would be concentric circles, the common center (epicenter) being located vertically above the focus. In practice this is not the case, especially because the Earth's crust has a complex structure. For many earthquakes, isoseismal maps exhibit great irregularities due to the heterogeneity of the underground.

The advantage of using this fact to investigate the subsurface geology was emphasized by SIEBERG [1923, pp. 105-110], who advanced useful suggestions. This paper is also an attempt to fulfill that purpose.

Theoretical intensities--To calculate the theoretical intensities with which the observed values will be compared, we need first to adopt an equation connecting the earthquake intensity (or the maximum ground acceleration) with the epicentral distance. Most of the equations already proposed may be reduced to the form

$$a\,(\Delta^2 + h^2)^p = K \qquad (1)$$

where

a = maximum ground acceleration
Δ = epicentral distance
h = focal depth
p and K = constants

On the other hand, the intensity I (on the Mercalli Scale) and the maximum ground acceleration (in gals) are connected by Cancani's law

$$I = m + 3\log_{10} a \qquad (2)$$

where m is a constant.

Eq. (1) and (2) combine into

$$I + 3p\log_{10}(\Delta^2 + h^2) = m + 3\log_{10} K \qquad (3)$$

K is characteristic of every shock. For the other constants the writer preferred the values proposed by GUTENBERG and RICHTER [1942], the intensity being expressed on the Modified Mercalli Scale of 1931. These values are $p = 1$ and $m = 1.5$, with which (3) becomes

$$I + 3\log_{10}(\Delta^2 + h^2) = 1.5 + 3\log_{10} K \qquad (4)$$

Substituting in this equation the 'observed' I and Δ, we can find the parameters h and K, which give the best adjustment.

For this purpose an approximate least-squares solution was previously used [MACHADO, 1949]. But now a nomogram (Fig. 1) has been worked out, where (4) is represented by a straight line, permitting a graphical treatment of the subject.

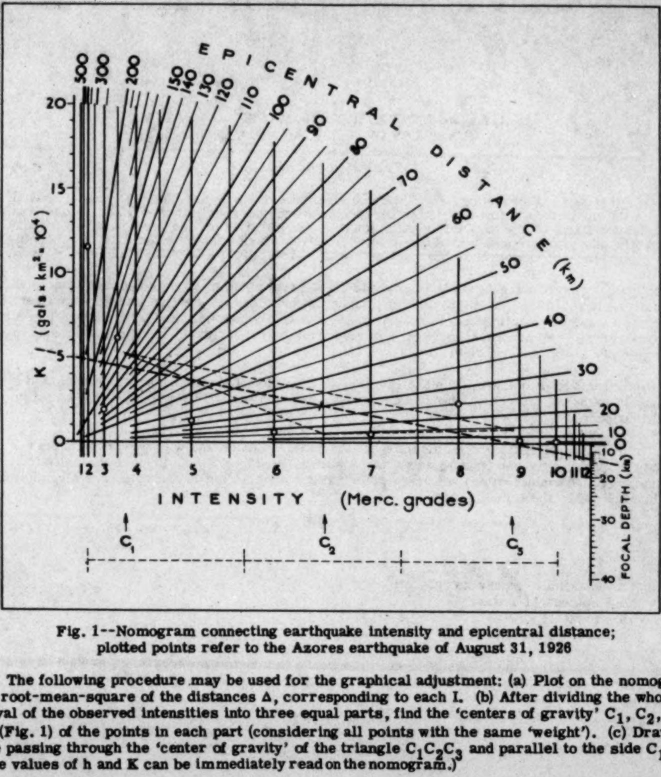

Fig. 1--Nomogram connecting earthquake intensity and epicentral distance; plotted points refer to the Azores earthquake of August 31, 1926

The following procedure may be used for the graphical adjustment: (a) Plot on the nomogram the root-mean-square of the distances Δ, corresponding to each I. (b) After dividing the whole interval of the observed intensities into three equal parts, find the 'centers of gravity' C_1, C_2, and C_3 (Fig. 1) of the points in each part (considering all points with the same 'weight'). (c) Draw a line passing through the 'center of gravity' of the triangle $C_1C_2C_3$ and parallel to the side C_1C_3. (The values of h and K can be immediately read on the nomogram.)

The least-squares method is much more laborious, and accuracy is usually not improved. Having obtained the parameters h and K, (4) gives the 'theoretical' values of I, corresponding to each Δ, and the anomalies can be defined as

$$\delta I = I_{ob} - I_{th} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

subscript ob and th denoting the observed and theoretical values, respectively. (I_{th} or even δI can also be determined directly from Fig. 1.)

Instead of the intensity anomalies, SIEBERG [1923, p. 162] preferred the use of Reid's foundation (untergrund) coefficients $n = a_{ob}/a_{th}$ (a_{ob} and a_{th} being, respectively, the observed and theoretical maximum ground acceleration). But these coefficients are equivalent to the anomalies, since by (2) and (5) we have

$$\delta I = 3 \log_{10} (a_{ob}/a_{th}) = 3 \log_{10} n \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

Interpretation of the anomalies--In active volcanic regions like the Azores, according to a number of volcanologists, there must exist magma chambers which are frequently small reservoirs intruded in the upper crust of the Earth [VON WOLFF, 1914; SAPPER and Others, 1931; DALY, 1933]. The absorption of earthquake energy, by such magma chambers, appears to be an acceptable cause for the intensity anomalies.

Absorption is capable of a convenient theoretical treatment, if we assume that its effect on the ground acceleration is represented by a factor

$$\exp\left(-\int_0^D k\, dL\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

in which

k = absorption coefficient
dL = differential of the path
D = total length of the path (from the focus to the surface)

Neglecting the absorption of the crust outside the magma chambers, the integral of (7) reduces to kL, k being now an average absorption coefficient of the magma, and L the length of the path of a seismic ray within the chamber.

Assuming further that the theoretical accelerations correspond to the absence of magma chambers, we have

$$a_{ob} = a_{th}\, e^{-kL}$$

whence

$$\log_{10}(a_{ob}/a_{th}) = -\,0.43\ kL$$

and by (6)

$$\delta I = 3\log_{10}(a_{ob}/a_{th}) = -\,1.3\ kL \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

In addition to absorption, there are other causes contributing to the anomalies. Errors of assignment of the intensity may account for deviations which usually do not exceed 0.5 Mercalli grade.

More uncertain is the influence of reflection and refraction of the waves at the boundaries of magma chambers (and at other discontinuities). When absorption is preponderant, we should approximately compensate that effect (due to reflection and refraction) if, by an adequate choice of k, we could make the computed δI correspond to a given value of L. Unfortunately, a previous knowledge of L is rather difficult in most cases.

Finally we must remark that the assumption of absorption being the main cause of the anomalies implies that these anomalies be mostly negative. This depends evidently on the chosen theoretical values of the intensity, which we identified with the intensities in a crust without magma chambers.

The proposed graphical method exaggerates, for adjacent values of I, the influence of points with larger epicentral distance, thus providing a greater frequency of negative anomalies. A convenient choice of k would again compensate, to some extent, the possible remaining deviation of the theoretical values.

Anomalies of an Azorean earthquake--As an example of application the writer chose the Azores earthquake of August 31, 1926, of which AGOSTINHO [1927] accomplished a careful field investigation (see Fig. 2). In his report the intensities are rated on the Mercalli-Sieberg Scale; but as no substantial difference exists between this and the Modified Mercalli Scale of 1931, (4) will hold as well for those values.

In the same study the epicenter was located at 38°32'N, 28°35'W, and Table 1 gives assigned intensities at the various places and the corresponding distances to that epicenter.

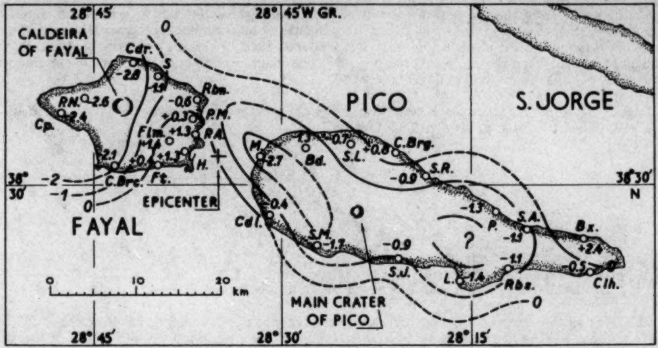
28° 45
28° 45 W GR.
CALDEIRA OF FAYAL
Cdr.
S
-2.8
1.9
Rbn.
RN.
2.6
2.4
Cp.
-0.6
+0.3
P.M.
Flm.
+1.3
R.A.
+1.6
2.1
+0.4
+1.3
H.
C.Brc.
Ft.
38° 30
-2
-1
0
EPICENTER
FAYAL
0
10
20
km
28° 45'
28° 30'
PICO
S. JORGE
M.
2.7
1.3
Bd.
0.7
S.L.
+0.8
C.Brg.
S.R.
-0.9
38°30' N
0.4
Cdl.
-1.3
P.
S.A.
-1.1
Bx.
+2.4
S.M.
-1.7
-0.9
?
-1.1
-0.5
Clh.
S.J.
L.
1.4
Rbs.
0
MAIN CRATER OF PICO
28° 15'

Fig. 2--Lines of equal intensity anomaly of the Azores earthquake of August 31, 1926

Table 1--Intensities and epicentral distances of the Azores earthquake of August 31, 1926

No.	Location	I_{ob}	Δ
		gd[a]	km
	Fayal Island		
1	Horta	10	4
2	Flamengos	10	6
3	Praia do Almoxarife	10	4
4	Feteira	9	7
5	Pedro Miguel	9	5
6	Ribeirinha	8	7
7	Salão	7	12
8	Castelo Branco	6	12
9	Capelo	5	19
10	Praia do Norte	5	17
11	Cedros	5	15
	Pico Island		
12	Candelaria	8	9
13	Canada da Bragada	8	21
14	Baixa	8	44
15	Bandeiras	7	10
16	Santa Luzia	7	16
17	Madalena	6	5
18	S. Roque	6	25
19	S. João	6	25
20	S. Mateus	6	16
21	Prainha	5	33
22	Santo Amaro	5	37
23	Ribeiras	5	37
24	Calheta	5	46
25	Lagens	5	32
26	S. Jorge Island	5	50
27	Graciosa Island	3	80
28	Terceira Island	3.5	120
29	S. Miguel Island	2	285

[a] Grades of the Mercalli-Sieberg Scale.

Using the proposed graphical method (see Fig. 1), we find h = 13 km, and $K = 5.0 \times 10^4$ gals×km^2. With the theoretical intensities obtained from the nomogram, we can also compute the anomalies shown on Figure 2; we note immediately that most of these anomalies are much greater than the possible errors of assignment of the intensities (which seem to be less than 0.5 Mercalli grade).

We shall now assume that only the negative anomalies are significant, and are caused by magma chambers. It is also reasonable to admit a vertical correspondence of the centers of the chambers to the craters of the main volcanoes of Fayal and Pico Islands. This condition can be satisfied by assuming a mean depth of the magma chambers of about five km; and for this depth the approximate subsurface map of Figure 3 was outlined.

We ignore the true thicknesses of the chambers. Using the arbitrary value $k = 0.5\ km^{-1}$, with which (8) becomes $\delta I = -0.65\ L$, and neglecting refraction, the diagramatic section of Figure 4 was drawn, but the thicknesses indicated are obviously uncertain.

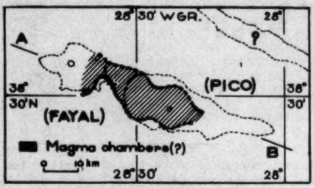

Fig. 3--Subsurface map (depth five km) showing magma chambers (?) below Fayal and Pico Islands

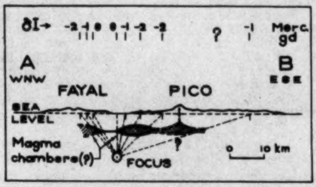

Fig. 4--Diagramatic section through Fayal and Pico Islands (compare with Fig. 3)

There appear to exist three interconnected reservoirs of magma, one corresponding to Fayal, another to Pico, and a third partially below Fayal-Pico Channel with no apparent associated volcano.

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ON THE HOMOGENEITY, OR OTHERWISE, OF THE EARTH'S UPPER MANTLE

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Abstract--The question of the extent of inhomogeneity between the Earth's crustal layers and a depth of 1000 km is discussed. On the basis of the author's Model A, inhomogeneity would be spread over a range of several hundred kilometers below a depth of 200 km, while with Model B there could be homogeneity between depths of 200 and 2700 km. Thus Model B is less incompatible with cyclic convection current theories than Model A. If reliable evidence for convection currents in the mantle should ever emerge, this would give some support to Model B, and, indirectly, to the existence of a solid inner core. Also should Model B prove to be nearer the truth than Model A, this would reduce certain of the difficulties in the way of convection current theories.

The question of the homogeneity of the Earth's mantle below the Mohorovicić discontinuity has lately become of some importance in relation to various theories of convection currents in the mantle. In this paper we shall be concerned with the region between the crustal layers and a depth of 1000 km, and, for brevity, shall refer to this region as the upper mantle. The term homogeneous will be used to refer to a region in which there are no changes in chemical composition or polymorphic transitions; there will, however, be density changes in such a region arising from variations of pressure and temperature.

BIRCH [1952] in his comprehensive study of the Earth's elasticity inferred that the rate of increase of the seismic velocities between depths of 200 and 900 km is too great for this region to be homogeneous in the above sense. This inference has been questioned by VERHOOGEN [1953], who considers that uncertainties in parts of the data on silicate rocks used by Birch do not warrant the drawing of any certain conclusion. The present writer is not qualified to assess the relative strengths of the arguments of Birch and Verhoogen, but it would appear that further evidence is desirable before it can be asserted categorically that the Earth's mantle is not homogeneous.

BIRCH [1954] has, in fact, since drawn attention to a previous quite independent argument of BULLEN [1936, 1940] implying inhomogeneity above a level of 1000 km. In the course of constructing Model A [for summary, see BULLEN, 1953, pp. 212-219], it was found that the impossible value of 0.57 Ma^2 for the moment of inertia of the central core was indicated (M and a being the mass and radius of the central core), unless either the density just below the crust is markedly greater than the assumed value of 3.32 gm/cm^3, or else that there is, in the mantle, marked inhomogeneity which would have to be located a long way above the core. Strong evidence was produced against raising the assumed figure of 3.32 to the value of 3.7, which, as Birch states, is the minimum value formally required to bring the moment of inertia of the core down to below 0.40 Ma^2 if the mantle is to be assumed homogeneous.

The purpose of the present note is to discuss this argument in a little further detail.

Looked at from the broad thermodynamical viewpoint, the variation of the density ρ at depth z in the Earth (here treated as spherically symmetrical) is given by

$$\frac{d\rho}{dz} = \left(\frac{\partial\rho}{\partial p}\right)_{S,n_i}\frac{dp}{dz} + \left(\frac{\partial\rho}{\partial S}\right)_{p,n_i}\frac{dS}{dz} + \Sigma_i\left(\frac{\partial\rho}{\partial n_i}\right)_{S,p}\frac{dn_i}{dz} \quad \ldots\ldots\ldots (1)$$

where p and S denote the pressure and entropy, and the n_i are parameters specifying the phase and the chemical state. The first of the three terms on the right-hand side of (1) gives the expression previously used by BULLEN [1936], namely $g\rho^2/k$, where g is the gravitational acceleration at depth z, and k is the adiabatic incompressibility.

BIRCH [1952] has examined the correction, δ say, arising from the presence of the second term in (1) and has shown that the first two terms on the right-hand side of (1) are equivalent to

$$(g\rho^2/k)\,(1 - \delta) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where

$$\delta = \gamma\, c_p\, \tau/g \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

In (3), γ is Grüneisen's parameter, c_p is the specific heat at constant pressure, and τ is the excess of the actual temperature gradient in the Earth over the adiabatic gradient. (In the Appendix of the present paper, (2) and (3) will be derived a little more rapidly than in the procedure in Birch's paper.) Birch has shown that allowance for the term δ in (2) would be in the direction of increasing, and not decreasing, the impossible coefficient 0.57, and concludes that the last term in (1) must be significant in the outer mantle.

This series of evidence appears in fact to be overwhelmingly in favor of inhomogeneity in the upper mantle. But there is room for some further discussion on the extent of such inhomogeneity, since a satisfactory moment of inertia for the core can be derived by various types of density adjustment in the upper mantle.

Details of the seismic velocity gradients between 200 and 1000 km are still a matter of controversy among seismologists, but there is fairly general agreement that there is a considerable range inside this range of depth in which the gradients are much higher than those below 1000 km. Granting that the existence of inhomogeneity above 1000 km is well established, it is then to be expected a priori that the density gradient will be abnormally great where the velocity gradients are abnormal. This was the principle used in constructing Model A, in which the inhomogeneous part of the upper mantle was placed at depths between 400 and 1000 km, in line with the velocity data used.

Since the p and S velocities are functions of k and the rigidity μ, as well as of ρ, it is of course formally possible that the velocity abnormalities throughout a good part of the upper mantle are due to abnormalities in the behavior of k and the rigidity μ, rather than of ρ. Such a possibility would need to be considered if evidence from other sources should arise pointing that way, and in this connection the writer's second Earth model, Model B [BULLEN, 1950], becomes of some interest.

In Model A, it had emerged that the incompressibility k was nearly continuous across the boundary between the base of the mantle and the top of the central core; the formal figures showed a drop from 6.5×10^{12} to 6.2×10^{12} dyn/cm^2. It is not to be expected a priori that k would drop in value across the boundary, and, moreover, the estimated drop of five per cent could arise from uncertainties in the postulates underlying Model A. In addition, the gradient dk/dp was not detectably different on the two sides of the boundary. Model B was then constructed on the postulate that k is indeed continuous across the boundary and smoothly-varying in the whole Earth below a depth of 1000 km. Use was made of seismic data in the lower mantle (actually, in the region D$''$) and in the outer core (the region E). But seismic data were not used to calculate the density above the top of D$'$ at a depth of 1000 km; nor was any starting value of ρ assumed at any point affecting the density distribution below 100 km.

In spite of the reduction in k at the core boundary being only five per cent, it proved possible to eliminate this discontinuity only by having higher density values between depths of 100 and 1000 km than in Model A. Whereas the density in Model A falls relatively rapidly with decreasing depth above 1000 km, it was found necessary in constructing Model B to keep the density gradient for a considerable distance above 1000 km practically the same as in the part D$'$ of the lower mantle. On the formal calculations the gradient remained steady right up to a depth of 80 km, the formal density found at this level being 3.8 gm/cm^3.

There are various grounds, including evidence on the mean density of the Moon, for assuming that the density in the Earth remains of the order of 3.3 to 3.4 gm/cm^3 down to a depth of 150 to 200 km. This indicates that Model B needs a correction in the direction of reducing the density formally derived at levels above 200 km. Such a correction can be made in various ways without departing too seriously from the assumptions underlying Model B. But a calculation shows that the essential compressibility-pressure postulate underlying Model B is incompatible with the existence, anywhere between depths of 200 and 1000 km, of density gradients seriously exceeding those in the region D′. Thus Model B is broadly compatible with homogeneous conditions between depths of 200 and 2700 km. The rigidity, and most probably the incompressibility, would of course have to change even more rapidly between 200 and 1000 km than in Model A in order to fit the seismic velocity data. On Model B, the main inhomogeneity in the mantle would then be associated with a sharp change in density or density gradient at a depth not appreciably greater than 200 km.

Now deviations from homogeneity at depth within the Earth, especially in respect of chemical constitution, must not be too great if cyclic convection currents are to occur in the Earth's mantle. Hence, if it be assumed that a steep density gradient near 200 km is no barrier to convection currents below this level, then Model B is more compatible with the possibility of cyclic convection currents than is Model A. The interesting situation thus appears to emerge that should reliable evidence of the existence of cyclic convection currents in the mantle be forthcoming, then this would give some support to Model B, and therefore, indirectly, to the compressibility-pressure hypothesis, to the solidity of the inner core and to other properties associated with Model B.

The writer does not believe that, on present evidence, it is possible to discriminate between Models A and B. But so long as Model B continues to claim attention, it would seem unwise to assume the presence of inhomogeneity below a level of order 200 km in the Earth.

It may be remarked that one way of making the correction to Model B indicated a little earlier is to assume that there are ranges of depth below 200 km where the density gradient is actually less steep than for a homogeneous material. Such a hypothesis has some interesting properties that are being examined by the writer at the present time. In particular, the slow removal of an abnormally low density gradient over a period greater than the age of the Earth offers an interesting compromise between the usual cyclic convection theories and theories which admit no convection.

APPENDIX

The following is an alternative method of deriving (2) and (3), which are relevant to a homogeneous region. The adiabatic compressibility k is given by

$$\left(\frac{\partial \rho}{\partial p}\right)_S = \frac{\rho}{k} \quad \ldots\ldots (4)$$

where S, as earlier, denotes the entropy. If τ is as earlier defined, and T denotes the temperature, we have

$$\tau = \frac{dT}{dz} - \left(\frac{\partial T}{\partial p}\right)_S \frac{dp}{dz} = \left(\frac{\partial T}{\partial S}\right)_p \frac{dS}{dz} \quad \ldots\ldots (5)$$

The coefficient α_p of thermal expansion at constant pressure is given by

$$\alpha_p = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p \quad \ldots\ldots (6)$$

By (5) and (6)

$$\tau = -\frac{1}{\rho\alpha_p}\left(\frac{\partial \rho}{\partial S}\right)_p \frac{dS}{dz}$$

Hence, from (1), ignoring variation of the n_i, and using (4), we have

$$\frac{d\rho}{dz} = \left(\frac{\partial \rho}{\partial p}\right)_S \frac{dp}{dz} + \left(\frac{\partial \rho}{\partial S}\right)_p \frac{dS}{dz} = (\rho/k) \times g\rho - \rho\alpha_p\tau = (g\rho^2/k)(1 - \delta)$$

where

$$\delta = \alpha_p k\tau/g\rho \quad \ldots\ldots (7)$$

On introducing Grüneisen's parameter γ, defined by

$$\gamma = \alpha_p k/\rho c_p$$

it is seen that (7) is equivalent to (3).

The writer wishes to thank B. Gutenberg for kindly making available to him the facilities of the Seismological Laboratory of the California Institute of Technology during the preparation of this paper, and the United States Educational Foundation in Australia for kindly providing assistance in the form of a Travel Grant to California.

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DISCUSSION OF

"THE RADIOACTIVITY OF BOTTOM SEDIMENTS IN CHESAPEAKE BAY"

by GILBERT JAFFE and JAMES H. HUGHES

[Trans., v. 34, pp. 539-542, 1953]

Bert C. Aschenbrenner (Research, Inc., Dallas, Texas)--The method and results described in the paper are indeed interesting. However, there appear to be some disadvantages which are herewith considered.

Since the authors state in the introduction that one aspect of their investigation is to gain some idea of the 'background' (activity of the samples in their natural, normal state), consideration of the

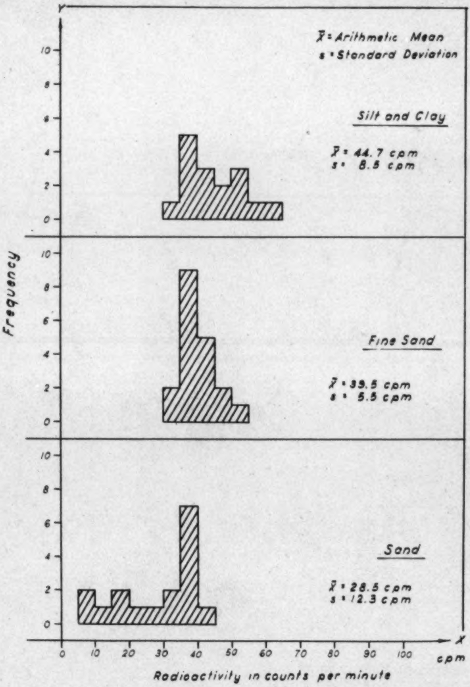

Fig. 3--Frequency distribution of the counts equilibrium conditions is thought to be of prime importance. If reproducible results are desired, the uranium and thorium in the sample should be in radioactive equilibrium with their daughter products when the sample is counted, especially since the rate of diffusion of radon and thoron is evidently high for loose, fine-grained sediments. In order to eliminate the error introduced by the high emanating power of the more active sediments, it is suggested that the samples be sealed for 30 days after they have been disaggregated and dried [BEERS and GOODMAN, 1944; YAGODA, 1949].

If the radioactivity of a sample is expressed in counts per minute, it is difficult to evaluate the significance of the results and compare them with the observations of other investigators. The following ways of expressing radioactivity, listed in the order of the writer's preference, are thought to render a more satisfactory basis for evaluation and comparison: (1) equivalent grams of radium per gram of sample; (2) counts per minute per gram of sample; and (3) counts per minute per unit surface area of sample. It is also suggested that it be indicated whether or not the results have been corrected for factors inherent in the equipment such as self absorption in the window and in the source, and counting geometry.

Neither the large standard deviations nor the frequency distribution of the counts (see Fig. 3) suggests at first glance that the activities of the three particle-size groups are significantly different. Since the difference in the arithmetic means is used as the expression of the definite correlation between radioactivity and the type of sediment, it is suggested that it be stated on what basis it was concluded that the means differ significantly (results of t-test, analysis of variance or whatever test the authors used).

The results of the investigation by Jaffe and Hughes are apparently in agreement with the observations of BEERS and GOODMAN [1944], EVANS, KIP, and MOBERG [1938], and others with regard to the correlation between radioactivity and type of sediment. One looks forward with interest to the collection of more data on the radioactivity of shelf sediments and their comparison with the radioactivities of probable parent materials.

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Gilbert Jaffe (U. S. Navy Hydrographic Office, Washington 25, D. C.) and James H. Hughes (Office of Naval Research, Washington 25, D. C., Authors' closure)--We appreciate Aschenbrenner's interest in our paper.

The samples of sediment from Chesapeake Bay were the first we have used for the measurement of radioactivity. They were used merely for preliminary survey and were not sealed for 30 days prior to counting. The activity was measured shortly after disaggregating and drying the samples. It is planned, however, to age future samples under seal before measuring their activity.

The Geiger tube which was used to count the samples had an outside diameter of 1.8 cm and an exposed height of ten cm. The samples completely covered this area of 56.5 cm^2. Therefore, if the counts per minute of the samples in Table 1 of the paper are divided by this area, the measure of activity obtained will be counts per minute per unit surface area of sample. This measure is third in Aschenbrenner's order of preference. We cannot express the activity of the samples according to his first or second preferences because the samples were not weighed. No corrections were made for inherent errors, self absorption, or counting geometry because we felt that an absolute disintegration rate was not required for a comparison survey.

At the time the paper was written it was assumed that there was enough difference between the means of the various types of sediment to say that they differed significantly. Since Aschenbrenner raised the question as to whether the samples do in fact differ significantly, the sediments were subjected to mechanical analysis and median diameters determined. A scatter diagram of the results (see Fig. 4) indicates a reasonably strong tendency for radioactivity to vary with grain size. The wide variation of counts per minute in sediments with the same median diameter can be attributed to varying quantities of unlike minerals and the fact that the median diameter does not reflect the asymmetry of each sample's grain-size distribution.

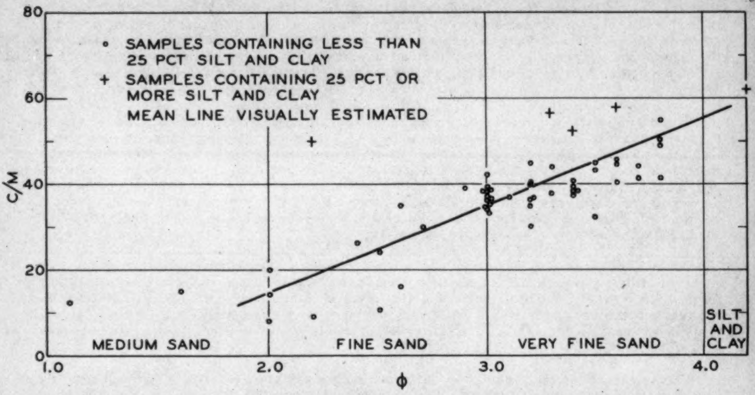

Fig. 4--Scatter diagram of the relationship of counts per minute to median diameter (ϕ units)

From the original paper we omitted due credit to Frank Senftle and Francis Flanagan of the U. S. Geological Survey for their suggestions on the basic design of the counting chamber and generous assistance. We wish to correct this omission now.

NOTES AND PERSONALIA

(See also pp. 862-864)

NOTES

Conference of Dallas Council on World Affairs, November 15-17, 1954--On November 15-17, 1954, the Dallas Council on World Affairs will hold an important conference on the raw-material needs of the United States now and in the future at which Stockpiling for National Defense will be the subject of the address of Arthur S. Flemming, Director of the Office of Defense Mobilization. Addresses and panels on oil and gas topics will be featured prominently, with authorities in the field leading the discussions. Individuals and organizations interested in attending the conference should write for more detailed information to the Dallas Council on World Affairs, 2419 Maple Avenue, Dallas, Texas. The conference will immediately precede the Dallas meeting of the Midwestern Section of Society of Exploratory Geophysicists on November 18 and 19.

Zeitschrift für Kristallographie--After an interval of almost ten years, publication of the Zeitschrift für Kristallographie will be resumed. The publishers, Akademische Verlagsgesellschaft, m.b.H., Frankfurt am Main, announce that Volume 106, Number 2, will be released during October, 1954. Professors M. J. Buerger (Massachusetts Institute of Technology), F. Laves Mineralogisch-petrographisches Institut der Eidg. Techn. Hochschule, Zurich), G. Menzer (Universitätsinstitut für Kristallographie und Mineralogie, München), and I. N. Stranski (Technische Universität, Berlin-Charlottenburg) will serve as editors of the journal. Articles will be printed in German, English, French, and Italian.

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REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

FEINBERG, J. G., The Atom Story, Philosophical Library, New York, 243 pp., 1953, $4.75.
HEISENBERG, W., Nuclear Physics, Philosophical Library, New York, 225 pp., 1953, $4.75.

Both of these books present the subject matter of atomic and nuclear physics for the nonspecialist, and although both might be said to culminate with the development of the atomic fission bomb, Heisenberg remains aloof from broad consideration of the impact of this discovery upon man and society, while Feinberg is deeply concerned with all of its implications.

The Atom Story is written in novelistic style with, for this reviewer at least, an oversupply of fanciful analogies and perhaps of moralizing too. No doubt this springs from an attempt to inform and convince the reader who has no scientific background whatsoever. It must be admitted that in this attempt the book succeeds quite well. It is easy to read, is particularly good in organization, and it concludes with a reprint of a pamphlet of the Civil Defense Office entitled Survival under Atomic Attack which everyone should read. Feinberg corrects one prevalent notion of the destructive power of hydrogen bombs as against atomic bombs which warrants mention. He recognizes that a thousand-fold increase in power means only an increase in the radius of destruction by a factor of ten, but reminds us that the area of destruction increases by a factor of 100.

Nuclear Physics, based originally on a series of lectures for scientists with no training in theoretical physics, is naturally less fulsome and more academic in style. More detailed discussions of nuclear research are presented after a much more concise, yet complete, historical development. A most interesting feature is the appendix on German research into applications of atomic energy which answers the question of the German failure to obtain an atomic bomb. There is no discussion of the fusion or hydrogen bomb.

ALFRED D. SOLLINS

HASSMANN, H., Oil in the Soviet Union: History, Geography, Problems, Princeton University Press, xvi + 173 pp., 1953, $3.75 (translated from the German by A. M. Leeston).

E. De Golyer, dean of American petroleum geologists, stresses in the book's foreword that during World War II the Soviets were more interested in the petroleum technology of the West than in the very material assistance rendered in the form of lend-lease refineries. De Golyer further notes that Hassmann's work, supplemented by the translator's addition of many notes, the latest statistics, and a bibliography, makes this book the best general survey of the Russian oil economy presently available.

The book is split into three parts: the basis, the development, and the regions of the Soviet oil industry. In order to place this industry in proper perspective, Hassmann devotes 18 pages to describing the Russian economic regions and system. Marx's 'historical materialism' requires that material life takes precedence over spiritual life, and that all sensations, concepts, and comprehensions be traced back to matter. Accordingly, socialistic heavy industry is being developed to give 'capitalism the death blow economically'; this economy is, of course, planned by the state and managed from the top down.

At the turn of the century, Russia surpassed the United States in oil production, although before and after this period the United States led the world. Under the czars, oil development was markedly hampered by legislation; however, the fabulous richness of the Baku region, with its 22 commercially productive horizons, attracted European and American capital, and these operators came to dominate all the Russian oil regions.

The Soviets reorganized the oil industry into a series of trusts and groups directed by the Federal Ministry of Petroleum Production. While these organizations have not invented or developed new methods of exploration, new methods of the Western World have been adopted as soon as their economic validity was established. By 1947, 75 pct of the Soviet Union is said to have been geologically explored. Today, more than a thousand geological-geophysical prospecting parties are operative in the USSR, a magnitude of effort favorably comparable on an area basis to that exerted by the non-Soviet bloc. Similarly, the Soviet record for deep drilling exceeded 16,700 ft in early 1950 at a time when the world's deepest well was 20,551 ft in Wyoming. Offshore drilling is also commonplace in Russia, 20 wells having been drilled off Baku in 1950. Current estimates place the Russian refining capacity at about 700,000 barrels daily, as compared to a daily consumption by the United States of about 8,000,000 barrels. Several natural gas lines over 500 mi in length have also been constructed over difficult terrain.

Regionally, the Soviet Union, with an area covering one-sixth of the continental surface of the globe, has about one-tenth of the total proved reserves of world oil. Hassmann briefly sketches the history, geological structure, production figures to date, transportation, and refining facilities of each of Russia's major oil districts. It is interesting to note that the Second Baku, a region about the size of Spain, has a name that is primarily propagandistic, being coined in the hope that an oil district would be discovered that could rank with the original Baku region.

In discussing problems facing the Russian oil industry, Hassmann notes that because the Soviet supplies with coal or electricity a large part of the energy obtained from petroleum under the modern capitalistic system, he is forced to hedge as to whether the Russian oil supply is the Achilles' heel of the Soviet economy as other writers have suggested. Russia's present peacetime economy requires forced imports from such satellites as Rumania, Austria, Hungary, and Albania, even with curtailment of civilian consumption. Despite great efforts, Russian petroleum science and technology still remain far inferior to that of the United States. Hassmann concludes in his epilogue that the enormously rich Middle East oil region, where there exists 55 pct of the world's known oil reserves, is actually the key to Russia's expanding search for petroleum if Soviet military and economic capabilities are to surpass the accomplishments of capitalistic Western society.

CHARLES C. BATES

TAYLOR, GRIFFITH (ed.), Geography in the Twentieth Century, A Study of Growth, Fields, Techniques, Aims, and Trends, Philosophical Library, New York, and Methuen, London, 2nd ed., xi + 661 pp., 1953, $8.75.

Griffith Taylor of Australia and Canada has brought together in this symposium a pot pourri of geographical essays, into which one can dip with the assurance of always coming up with toothsome chunks of meat if not with a completely balanced diet. The volume aims, among other things, to set forth the salient features of modern geography and to show how geographers' ideas have changed during the past 50 years as to what are the important fields of their discipline.

The 28 chapters by 22 authors, mostly British and American, include some masterly essays and some surprising gaps. There are no chapters on economic geography or historical geography, and chapters on only limited aspects of climatology. The editor states that the inclusion of a chapter on the sociological aspects of geography makes it unnecessary to include economic or historical geography. Yet J. W. Watson, author of the sociological chapter, specifically disclaims the very healthy fields of economic and historical geography as forming any part of his field of social geography. On the other hand, despite the negligible geographic significance of race, Taylor includes a chapter on racial geography.

The book is divided into three parts: Part I, dealing with the philosophy and evolution of geography; Part II, with the environment as a factor; and Part III, with special fields of geography. All parts will interest geographers; nongeographic readers of the Transactions are likely to find Part II to be closest to their interests. The range of subjects treated in Part II is indicated by the titles and authors of the chapters: Geomorphology, S. W. Wooldridge; Geographical Aspects of Meteorology, F. K. Hare; Climatic Influences, S. S. Visher; Soils, D. F. Putnam; Modern Pioneer Settlement, Isaiah Bowman; Geography and Arctic Lands, A. L. Washburn; Exploration of Antarctica, Griffith Taylor; Geography and the Tropics, Karl J. Pelzer; Geography and Regionalism, E. W. Gilbert; and Land-Use Surveys, Especially in Britain, L. Dudley Stamp.

Wooldridge modestly assures us that his chapter on geomorphology is "no more than a slight and allusive essay on a wide field, inevitably reflecting the interests and the ignorance of the writer." Yet all the chapters are interesting, and several impressed this reviewer as giving comprehensive, fresh, and vigorous digests of the progress and status of problems in their fields. In Chapter 10, Putnam has given us a much-needed succinct yet well-documented summary of worldwide development and present-day knowledge of soil geography, including soil conservation. The two regional chapters, 12 and 14, are original and stimulating. In Chapter 12, Washburn sketches not only arctic explorations but also the results of the explorations, and includes a valuable four pages on gaps in knowledge. In Chapter 14, Pelzer traces the economic-geographic development of the American, Asiatic, and African tropics, and analyzes the outstanding problems of African tropical agriculture today.

In Chapter 9, Climatic Influences, Visher is on solid ground when he discusses such matters as the effects of drought on livestock production. More questionable are rationalizations of less tangible effects blithely attributed to climate: that the high birth rate and ancestor worship of monsoon Asia result from droughts; that fluctuation of rainfall is partly responsible for recognition of God in arid regions; or that modern advanced civilizations owe their location in part to lack of seasonality of precipitation.

In Part I, G. Tatham, Chapter 6, Geography and Possibilism, defends the position of most present-day geographers, that man is free to choose a number of directions of development from among the possibilities offered by a given environment. This 'possibilism' is the antithesis of environmental determinism, and contrasts even with the mild determinism expressed by Visher and Griffith Taylor elsewhere in the volume. Editor Taylor enjoys a lively footnote duel with Tatham over this ancient bone of geographic contention (pp. 160-162).

Other noteworthy chapters in Part I analyze geography in the nineteenth century (Tatham), the French school of geography (R. J. Harrison Church), and the German school of geography (S. Van Valkenburg). The latter presents a graphic picture of the golden period of pre-Hitler geography, and of the tragic disintegration of the subject in the Haushofer-Nazi years. Geography of the Slavic countries is presented only for Czechoslovakia and Poland, apparently no one having been found to appraise the rich fields of Russian and Yugoslav geography.

Among the 12 chapters of Part III, the scholarly essay by J. K. Wright on the field of the geographical society deserves special mention. John Rose has a lucid chapter on the status of geography in Washington, D. C. Griffith Taylor devotes a chapter to describing his work in 'geopacifics,' or geography as a basis for peace, as a substitute for geopolitics, or geography as a tool to power. In his chapter on cartography, W. W. Williams might well add the useful world series of maps by the United States Air Force, on scales of 1/1,000,000 and larger, to the other sets of maps he lists. Incidentally, a subhead on page 617 refers to the 1/1,000,000 maps, originally conceived by the International Geographical Congress, as the International Map on the Scale of 1/100,000. A casual inspection reveals a good many other minor errors in the book, such as 'Otto' instead of 'Oscar' Schmieder (p. 104), misspelling of Kesseli (p. 167), and use of term 'valley breeze' for a nocturnal wind blowing from a mountain (p. 201). Chapter 28, Concise Glossary of Geographical Terms, has carried conciseness to the point of meaninglessness in all too many cases. To call 'pedalfer' merely "a major division of soils"; 'permafrost,' "frozen ground"; 'peneplain,' "an undulating rocky plain"; and 'playa,' "a salt lake," is to miss the essential character of these features. And if Pleistocene is "the last million years," and Pliocene is "a period about two or three million years ago," one wonders where to pigeonhole the intervening million years.

With all its unevenness, this book has many things to say to the geographer and geophysicist that have never been said better.

PEVERIL MEIGS

TURNER, FRANCIS J., and JEAN VERHOOGEN, Igneous and Metamorphic Petrology, 1st ed., 2nd impression, McGraw-Hill Book Co., ix + 602 pp., 1951, $9.00.

This treatise on petrology ranks with other classic texts in this field. The authors, who were trained in foreign schools, reflect their background in their treatment of the study of igneous and metamorphic rocks and in the references cited. They have, however, familiarized themselves with recent American research in the fields of petrology, geochemistry, and mineralogy. They have woven together the facts and themes of petrology to produce a well-integrated text. The book is not designed for beginners in this field but rather for the graduate student and the researcher.

This book contains novel approaches to petrology and it presents many problems to its readers. The modern trend, in applying thermodynamic theory to petrology, is stressed. The thermodynamic treatment includes some statistics and the newer developments of DeDonder, Prigogine, Defay, Guggenheim, and van Rysselberghe on irreversible processes. The concept of the phase rule and its application to systems of petrologic importance is presented in a single chapter as well as referred to in isolated instances elsewhere.

The eight chapters, which discuss the igneous rocks in the light of modern petrologic theory, are brilliant expositions of the genetic relationships of rock associations:

Chapter 6: Crystallization of basaltic and granitic magmas in the light of experimental data.
Chapter 7: The oceanic olivine-basalt trachyte volcanic association.
Chapter 8: Volcanic associations of nonorogenic continental regions, I, Associations with alkaline affinities.
Chapter 9: Volcanic associations of nonorogenic continental regions, II, Tholeiitic flood basalts and intrusive quartz diabases.
Chapter 10: Volcanic associations of orogenic regions.
Chapter 11: Basic and ultrabasic plutonic associations.
Chapter 12: The granite granodiorite plutonic association.
Chapter 13: Pegmatites, lamprophyres, nepheline syenites.

Chapter 14, The Environment, Origin, and Evolution of Magmas, represents the merging of petrology, geochemistry, and geophysics.

The section on metamorphism is based largely on the Memoir (No. 30 of Geological Society of America Series) by Turner on Mineralogical and Structural Evolution of the Metamorphic Rocks. One notes in this section also the increasing emphasis on the use of physicochemical theory in explaining the processes of metamorphism.

The last chapter, Metamorphism in Relation to Magma and to Orogeny, is well done. It deals chiefly with the source of heat for metamorphism and the problem of regional metamorphism.

This book is an outstanding work and geophysicists who read it will profit greatly from its contents.

GEORGE T. FAUST

PENCK, WALTHER, Morphological Analysis of Landforms, translated from the German by Hella Czech and Katherine C. Boswell, St. Martins Press, New York, 417 pp., 1953, $8.00.

This work, published originally in 1924 under the title Die morphologische Analyse, is well known to geomorphologists as a classic attempt to provide a theory of origin for the major landforms of the Earth. The original German text is exceedingly difficult reading for anyone who does not have a thorough knowledge of the language, and it is probable that few geomorphologists in America have read the complete work or have a first-hand knowledge of the entire argument. The present translation by Czech and Boswell is therefore a welcome addition to the literature, especially since it appears to be so carefully done, is clear, and is accompanied by a useful summary of Penck's main arguments prepared by Boswell.

Die morphologische Analyse was written by Penck a few years before his death in 1923 at the age of only 35. His purpose was to analyze crustal movements through the study of surface forms, and the work represents an ambitious undertaking for so young a geologist. Whether he succeeded in developing a useful method of analysis of crustal movements may be questioned, but the considerable interest his work has aroused among European and American geologists attests to its worth. His treatment of geomorphology is entirely theoretical and qualitative. It appears to be very much influenced by the work of W. M. Davis, in spite of the general view that it is a completely different concept.

The major argument may be divided into three parts. The first discusses weathering of rock material and the movement of weathered material on slopes. It is implied that mass movement of weathered material is the principal agent of denudation on slopes; and its importance seems to be essential to the later argument, for according to Penck, slopes develop upward from the rivers and the form is therefore dependent essentially on the rate of lowering of the river beds and the resistance of the weathered rock to the force of gravity. It now appears, however, that other processes such as sheet erosion, erosion by rills, and the splashing of rain drops in many places may be equally or more important processes. Penck appears to have been unaware of sheet erosion, and indeed there is much information on processes of erosion available now that was not known during Penck's lifetime.

The section of the work most familiar to American geomorphologists concerns the method of 'differential analysis' by which Penck develops slope forms. The degree of concavity or convexity of a slope is determined by the rate at which the local base level (generally a stream) is lowered or raised. The lowering of base level may accelerate or decelerate, depending on crustal movements.

If the lowering of base level accelerates, the removal of waste products from the lowest part of the slope will increase in rate. The increased rate of removal will gradually work upslope as the lower slope steepens, and evantually a slope that is convex to the sky results. Similarly a deceleration in the lowering of the local base level on a stationary base level will produce concave slopes. The effects of differences in rock types and climates are discussed. Penck's idea that breaks in slope, produced by changes in base level, work upslope and are preserved through long units of time has not been satisfactorily proved by many detailed studies of longitudinal stream profiles.

In the last part of the work many mountain ranges throughout the world are described and their forms analyzed to demonstrate that the analysis of form can be used to interpret the structural history of mountain ranges. This section of the work cannot be read critically by anyone who does not have an encyclopedic knowledge of the world's geology. On the other hand, Penck's discussion of the mountain ranges of America will probably not satisfy most American geologists.

Morphological Analysis of Land Forms, like Davis' work on the formation of the Appalachian Mountains, is now valuable principally because of its approach to morphological problems. Though the observations on which it is based and the conclusions arrived at may prove to be partly or entirely erroneous, the point of view will always be useful. Penck's insistence that geomorphology is a part of geology and not geography and that its most important goal relates to the interpretation of crustal movements and internal structure of the Earth is decidedly proper. The method of analysis, though anything but quantitative, is a considerable contribution and worth careful study. By making Penck's ideas available to many more geologists, the present translation should stimulate new ideas and new researches. We should be grateful to the translators and publishers for completing so well a valuable project.

JOHN T. HACK

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NOTES AND PERSONALIA

(See also p. 844)

NOTES

Corrigendum--In the issue of April, 1954, in the paper by John Northrop entitled Bathymetry of the Puerto Rico Trench, pages 221 to 225, the following acknowledgments should be added to those now shown on page 225: Acknowledgment is made to the U. S. Navy Hydrographic Office and to Maurice Ewing and B. C. Heezen of Lamont Geological Observatory of Columbia University for some of the sounding tracks that were used in the study.

Geophysical Conference, University of the Witwatersrand, Johannesburg--A Geophysical Conference for scientists in Southern Africa was held at the University of the Witwatersrand at Johannesburg, July 19-22, 1954. Over 40 papers were presented on (1) recent determinations of the ages of rocks and their geological implications, (2) geodesy, (3) crustal structure of the Earth including seismological and gravity investigations, (4) geomagnetism, (5) the mechanical properties of rocks including the phenomena of rock brusts, (6) the Earth's heat and its origins, (7) the interior of the Earth, and (8) geophysical prospecting.

Meeting of the American Meteorological Society--The American Meteorological Society will hold its 133rd National Meeting at Miami Beach, Florida, November 17-19, 1954. Details may be secured by writing to S. N. Ronning, Chairman, Committee on Publicity of the Miami Chapter of AMS, Pan American World Airways, Inc., P. O. Box 817, Miami 48, Florida, or to the Society's headquarters in Boston, 3 Joy Street, Boston 8, Massachusetts.

Instituto de Geofisica in Mexico--Word has come that as of June 1, 1954, the Instituto de Geofisica has been incorporated into the Ciudad Universitaria. The address is: Instituto de Geofisica, Torre de Ciencias 3er. piso., Ciudad Universitaria, Villa Obregon, D. F., Mexico.

Research grants of the National Science Foundation--The National Science Foundation has announced the making of 176 grants totaling more than a million dollars. These are chiefly for research. Among them are six grants totaling about $58,000 in the Earth sciences, eight grants in the engineering sciences, and four in physics. Among the general grants is one of $5100 to aid in the expenses of several delegates attending the Tenth General Assembly of the IUGG in Rome. Among the grants for research work in the Earth sciences is one of $20,000 to the Geophysical Institute of the University of Alaska for ionospheric research. In the engineering sciences, there is one of $13,000 for solar energy research at the University of Wisconsin.

Manpower resources in the geophysical sciences--The National Science Foundation has recently issued two releases in their Scientific Manpower Bulletins Nos. 3 and 4. These indicate the results of a survey carried on cooperatively with other agencies, breaking down the workers into various categories, and indicating pertinent statistical data with reference to the survey. The survey was based on the National Scientific Register of 1951.

World Symposium on Applied Solar Energy--A date in late fall of 1955 is being planned for a World Symposium on Applied Solar Energy to be held at Phoenix, Arizona, for which arrangements are being made by Stanford Research Institute, and which is sponsored by the Association for Applied Solar Energy organized in the Southwest in March, 1954. This first activity of the Association will bring together scientists and industrialists to evaluate present knowledge and to explore practical applications for solar energy, and to consider means of advancing knowledge of solar phenomena. This Symposium will be under the general chairmanship of Lewis W. Douglas, former Ambassador to Great Britain.

Acapulco Trench Expedition of Scripps Institution of Oceanography--An exploratory geological-geophysical expedition will be carried out by the Scripps Institution of Oceanography of the University of California during the fall and winter of 1954. The program will consist of two major parts, eupelagic studies and studies of the Acapulco Trench and the ocean to the westward. Robert L. Fisher has been designated scientific leader of the expedition.

PERSONALIA

William C. Ackermann has resigned his position as head of the Hydrology Section in the Hydraulic Data Branch of the Tennessee Valley Authority and has taken up duties as head of the newly formed Section of Watershed Hydrology of the Agricultural Research Service with headquarters in Washington.

Gregory Breit, Professor of Physics at Yale University, has recently been awarded an honorary doctorate by the University of Wisconsin.

Harrison Brown, Professor of Geochemistry at the California Institute of Technology, is on leave from his duties at the Institute and is on a six-month trip around the world making a survey of mineral resources. He plans to attend the Tenth General Assembly of the IUGG in Rome, spend several weeks in geochemical laboratories in England and on the Continent, and will complete his trip by stops in India and Japan.

Doak C. Cox of the Experiment Station of Hawaiian Sugar Planters Association has been elected Secretary of the Hawaiian Academy of Science.

Frank C. Foley has resigned his position with the Illinois State Geological Survey and has been named State Geologist and Director of the State Geological Survey of Kansas.

John W. Gabelman has resigned from his position as Geologist with the American Smelting and Refining Co. and has accepted a position as District Geologist with the Atomic Energy Commission. His headquarters will be in Grand Junction, Colorado.

Robert M. Garrels is to take up duties as Associate Professor of Geology at Harvard University in the fall of 1955 and will continue his work with the U. S. Geological Survey during the coming year. This is a correction to the news item on page 678 of the August issue indicating that he had already taken up duties at Harvard.

Joseph H. Goth, Jr., has resigned his work with Continental Oil Co. and accepted a position as Division Geologist, Rocky Mountain Division, with the Warren-Bradshaw Exploration Co. and will have his headquarters in Denver.

Herbert Hoover, Jr., formerly President of the United Geophysical Co., has been named Under Secretary of State. He recently had an important role in connection with the settling of the Anglo-Iranian oil dispute.

Alfred C. Ingersoll, Assistant Professor of Civil Engineering at California Institute of Tecnnology, is on leave for a year during which he will be teaching at Bengal Engineering College, District Howrah, Sibpur, West Bengal, India.

E. C. LaFond of the U. S. Navy Electronics Laboratory has been named Vice President of the Pacific Section of the American Society of Limnology and Oceanography.

Leonard B. Lipson, formerly Senior Research Physicist of Magnolia Petroleum Co., has taken up duties as Associate Professor of Petroleum Engineering at the University of Houston.

Raymond C. Moore, State Geologist of Kansas for 38 years and Chairman of the Department of Geology at the University of Kansas, has retired from those positions but will continue as Principal Geologist with the Kansas Geological Survey and Professor of Geology at the University.

George L. Pickard of the Department of Physics of the University of British Columbia has been named Secretary-Treasurer of the Pacific Section of the American Society of Limnology and Oceanography.

Oliver S. Reading, Captain of the U. S. Coast and Geodetic Survey and Chief of the Division of Photogrammetry, has retired recently after more than 39 years of service. He and his family will continue their residence in Washington, D. C.

Paul A. Rechard, formerly with the U. S. Bureau of Reclamation at Cody, Wyoming, has taken up duties as Chief, Water Resource Development, Wyoming Natural Resource Board, in Cheyenne.

J. M. Robertson, Professor of Engineering Research at Pennsylvania State University, has resigned to become Professor of Theoretical and Applied Mechanics at the University of Illinois.

Henry Salvatori, President of Western Geophysical Co. of America, has been elected a member of the Board of Directors of Consolidated Engineering Corp.

Thorndike Saville, Dean of Engineering of New York University, has received the 27th annual Lamme award of the American Society for Engineering Education.

Milner B. Schaefer of the Inter-American Tropical Tuna Commission with headquarters at Scripps Institution of Oceanography has been elected President of the Pacific Section of the American Society of Limnology and Oceanography.

Paul A. Smith, Captain of the U. S. Coast and Geodetic Survey, has retired after 30 years of service. During more recent years he has been United States Representative of the International Civil Aviation Organization, holding the temporary rank of Rear Admiral and with the designation as Minister. He and his family will continue their residence in Arlington, Virginia.

H. W. Straley, III, geologist and geophysicist of Princeton, West Virginia, has just completed a gravity investigation in southern Georgia.

John S. Sumner has completed his tour of active duty with the Marine Corps and has taken up work as a Research Assistant at the University of Wisconsin.

James S. Sweet is on leave from the U. S. Weather Bureau to take up duties at Rio de Janeiro, Brazil, in connection with Pan American Institute of Geography and History. In connection with his duties, he will teach courses in hydrology.

SPECIAL ANNOUNCEMENTS

Thirty-Sixth Annual Meeting, Washington, D. C., May 2-4, 1955--As announced in the August issue of the *Transactions*, the Thirty-Sixth Annual Meeting will be held in Washington, D. C., May 2-4 (Monday to Wednesday), 1955. Plans for the meeting are under way, and it is anticipated that all Sections will have sessions, as well as the Union as a whole. Place this meeting on your calendar and make plans to come.

This announcement serves also as an invitation for members and others to send word of plans for papers to be presented. Titles of papers with three copies of the abstract should be sent as soon as possible, not later than March 10, 1955, with advice concerning the time required (most papers are allowed from ten to 20 minutes) and the projection equipment needed. Send this word to the office of AGU at 1530 P Street, N. W., Washington 5, D. C., or to the Secretary or Program Chairman of the appropriate Section, as follows:

Geodesy	Frank L. Culley or Donald A. Rice (Program Chairman)	U. S. Coast and Geodetic Survey Washington 25, D. C. U. S. Coast and Geodetic Survey Washington 25, D. C.
Seismology	James A. Peoples, Jr.	39 Edgewater Drive Waltham 54, Mass.
Meteorology	Woodrow C. Jacobs	4302 Kentbury Drive Bethesda 14, Md.
Terrestrial Magnetism and Electricity	Leory R. Alldredge	3133 Jennings Road Kensington, Md.
Oceanography	Donald W. Pritchard	Chesapeake Bay Institute RFD 2, Box 426a Annapolis, Md.
Volcanology, Geochemistry, and Petrology	Felix Chayes or George S. Switzer (Program Chairman)	Geophysical Laboratory 2801 Upton Street, N. W. Washington 8, D. C. U. S. National Museum Washington 25, D. C.
Hydrology	Harry F. Blaney or Ralph N. Wilson (Program Chairman)	1509 P. O. and Court House Bldg. U. S. Dept. of Agriculture Los Angeles, Calif. 3322 Stanford Drive University Hill Hyattsville, Md.
Tectonophysics	James T. Wilson	Department of Geology University of Michigan Ann Arbor, Mich.

As the Section Secretaries reserve the right to close filled programs in advance of the date indicated, it is desirable that word concerning papers be sent in early. It is the plan to publish abstracts in the program. Remember that an abstract is an opportunity to bring the important results of your work to all who see the program. It must be concise, but comprehensive, and not exceed 200 words. Longer abstracts will be reduced to 200 words or omitted at the editor's discretion. Complete manuscripts of papers are not necessary, but are desired, and should be forwarded to the office of the Union by April 15, 1955. Indicate whether the paper is being submitted for the program only or also for consideration for publication in the *Transactions*. (Papers for publication only are also welcome for consideration for the *Transactions*.)

If a paper is written in collaboration, please indicate by whom it will be presented. Arrangements can usually be made with the Section Secretary or Program Chairman for presentation of papers by authors who are unable to attend, but papers to be presented by title only are not included in the program

The Chairman of the Committee on Meetings (John N. Adkins, 3609 Chevy Chase Lake Drive, Chevy Chase 15, Md.) invites suggestions and comments that will be helpful in planning this meeting. Especially invited are comments relating to papers and symposia bearing on more than one Section.

Make hotel or room reservations directly with the hotel of your choice at an early date. If you fail on the first attempt, bear in mind that advance bookings not taken up are canceled two weeks in advance and that a follow-up request in mid-April may bring the desired response. We are making block booking at two or three hotels again, an announcement concerning which will appear in the SPECIAL ANNOUNCEMENTS of the December 1954 issue of the *Transactions*.

John N. Adkins, Chairman
Committee on Meetings

Pacific Southwest Regional Meeting, University of California at Berkeley, February 4-5, 1955--Attention is called to the annual Pacific Southwest Regional Meeting to be held at the University of California at Berkeley, February 4-5, 1955. Plans call for participation by the Sections of Hydrology and Oceanography, and possibly Meteorology. Titles of papers and abstracts of 100 to 150 words should be forwarded promptly to the Program Committee Chairman, David K. Todd (Division of Civil Engineering and Irrigation, University of California, Berkeley 4, Calif.). Martin R. Huberty (Professor of Irrigation, University of California at Los Angeles) is Chairman of the Regional Committee, and J. W. Johnson (Professor of Engineering, University of California at Berkeley) is General Chairman for the Berkeley meeting.

North Central Regional Committee--The North Central Regional Committee has recently reorganized, holding its own elections, and for the second year of the current triennium, Marion C. Boyer, Professor of Hydraulic Engineering at the University of Iowa, has been named Chairman, and C. E. Lamoureux of the U.S. Weather Bureau in Des Moines has been elected Secretary-Tresurer.

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TRANSACTIONS
AMERICAN GEOPHYSICAL UNION

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ON THE CONTRIBUTION OF ALPHA RAYS FROM THE GROUND TO THE TOTAL IONIZATION OF THE LOWER ATMOSPHERE

Victor F. Hess and W. Dudley Parkinson

Abstract--Alpha-ray ionization is perhaps the most variable single component of the ionization of the lower atmosphere. Many measurements have been made to determine the ionization from airborne sources of alpha rays. This depends principally on the amount of radon and thoron in the atmosphere. An attempt is made here to evaluate the role of alpha rays originating from the surface of the ground and other naturally occurring surfaces. It was found that about ten per cent of the small ions observed at one meter above ground are originally produced at the ground and carried upward by convection.

The number of alpha particles emitted from the soil has never been determined. In an estimate of the contributions of alpha, beta, and gamma rays from the ground to the total ionization of the lower layers of the atmosphere, HESS [1934] put this contribution of the alpha rays tentatively as zero.

With the development of improved alpha-ray counting technique, it seemed feasible to carry out experimental tests with various rock samples, samples of clay, sand, loam, humus, leaves of plants, and blades of grass, in order to see if this effect (on the average overland) is really negligible. Over the oceans and over water in general, there is no doubt that the alpha-ray effect is zero. It is also zero when the soil surface is thoroughly wet or covered with snow.

In order to arrive at a representative value for the alpha activity of the common types of surface material, we made a series of measurements with a scintillation counter. The background of the instrument was determined using dunite as a source material. The uranium content of this is sufficiently low to be considered zero. The efficiency of counting was determined by measuring the activity of a piece of uranium metal foil. This varies slightly with the age of the phosphor coating, but has a mean value of 83 pct. The readings in Table 1 have been corrected for background and efficiency. They are expressed in counts per square centimeter by dividing by the effective area of the source (12.9 sq cm). Background counts are included to show the lower limit of possible measurement. The background is principally due to impurities in the phosphor.

Table 1--Measurements of alpha activity of common types of surface material with a scintillation counter

Source	Counts/hr sq cm	Number of observations
Shale	4.4	7
Acid igneous rock	10.5	22
Basic igneous rock	1.2	3
Soil	5.1	26
Turf (soil covered by grass)	1.9	6
Vegetation	0.5	9
Background	1.1	...

It is almost impossible to arrive at a meaningful average of these figures, taking into account the proportion of the surface of the Earth of each type. Instead of doing so, we shall use the figure 5.0 counts per hour per square centimeter as a representative figure. This applies to soils devoid of vegetation. To apply it to another type of surface, the result can be multiplied by the appropriate factor. For instance, the result for turf should be lower by a factor of about 2/5.

Each alpha ray produces between 1.25 and 2.7×10^5 pairs of ions. Some of them emerge from layers which are slightly below the surface, so we shall assume that each produces 10^5 ion pairs. We can take the figure for the number of ion pairs produced per second per square centimeter of surface to be $S_0 = (5/3600) \times 10^5 = 139$. The longest range of the alpha particles involved is 8.6 cm, so that we have an alpha-ionized layer a little less than ten cm from the ground. These ions are carried upward by the ever-present turbulent motion of the air (eddy currents). At the same time they undergo continuous recombination and the question arises whether any of these ions, produced at ground level by alpha rays from the ground, are able to reach the height of 100 cm from the ground where most atmospheric-electric measurements (for example, ion counts, conductivity measurements) are performed.

The theory of eddy diffusion is now well developed and has been applied by HESS and SCHMIDT [1918] and by SCHWEIDLER [1920, 1922] to the study of the vertical distribution of radioactive gases (radon, thoron) and their subsequent products in the atmosphere, and for the estimate of the transportation of positive space charge from near the ground to higher levels.

It is easy to develop the formulas for our case. We consider a column of air of 1 cm^2 cross section resting on the ground and call s the ion content of this column, per gram of air, as far as it is due only to the sporadic emission of alpha particles from radioactive elements in the ground. s will diminish with height on account of the recombination of ions of opposite signs. Schmidt's formula for the upward eddy diffusion current is $S = -A\,(ds/dh)$, where A is the coefficient of eddy diffusion ('Austausch coefficient'). Its dimension is $cm^{-1}\ g\ sec^{-1}$. S is the flux of ions upward from the ionized sheath of ten cm depth to higher layers, per cm^2 and per sec.

We consider a layer of air between the heights h and $h + \Delta h$ and calculate, for a column of 1 cm^2 cross section, by which amount the total number of ions in this column will change with time (time elements dt). From below there enter $dS = -A\,(ds/dh)\,dt$ ions per cm^2/sec, while $dS' = dS + (dS/dh)\,\Delta h$ ions leave upward from the upper boundary. Therefore, there remain within the column Δh: $dS - dS' = -(dS/dh)\,\Delta h = +A\,(d^2s/dh^2)\,\Delta h \cdot dt$. In the column itself there are $s\,\Delta h \cdot \rho$ ions (ρ = density of air), of which a certain number will disappear by recombination.

If we use Schweidler's 'linear recombination law' (which holds for atmospheric air containing nuclei of condensation), we know that the rate of production of ions q is proportional to the actual number of small ions present. In the equation $q = \beta n$, β is the 'coefficient of disappearance' of Schweidler and is analogous to the decay constant for radioactive substances. The reciprocal θ of β is the 'average life of an ion.'

Numerous measurements of β and θ have been made since [HESS, 1934], and it has been found that the average life of small ions depends on the number of nuclei and on their composition. It varies between about 10 and 300 sec for the free atmosphere. The average over sparsely populated land areas is about 60 sec.

Since $\beta = 1/\theta$ is equivalent to a 'decay constant' for a number of ions which disappear by recombination, we see that in the column Δh considered $\beta\rho s\,\Delta h \cdot dt$ ions will disappear by recombination within dt sec.

The total change of ion content of the column Δh within dt sec is $A\,(d^2s/dh^2)\,\Delta h \cdot dt - \beta\rho s\,\Delta h \cdot dt$ which, for the stationary state, must be zero. Thus we have

$$A\,(d^2s/dh^2) = \beta\rho s \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

The solution (taking $S = 0$ for $h = \infty$) is

$$S = S_0 \exp\left(-\sqrt{\rho\beta/A} \cdot h\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Therefore, the ion content, originating from the primarily ionized surface layer of 8.6 cm in height, will diminish with altitude according to an exponential law.

Next we have to consider the change of the eddy coefficient with altitude which, according to SCHMIDT [1925], follows the formula $A(h) = A(1)\,h^{6/7}$, where $A(1)$ refers to 1 cm above ground and $A(h)$ to h cm above ground.

It is well known that the coefficient of eddy diffusion A for altitudes of 100 m is of the order of 50 $cm^{-1}\ g\ sec^{-1}$, while near the ground it decreases to less than 1 $cm^{-1}\ g\ sec^{-1}$. SCHWEIDLER [1920] (assuming $A = 50$ at 100 m, which is a low estimate) computed for $h = 1$ cm, $A(1) = 0.0185$. From this the values shown in Table 2 of A between 10 and 100 cm above ground are computed. For our purpose, it will suffice to take from this an average for the space between 10 and 100 cm from the ground about 0.5 $cm^{-1}\ g\ sec^{-1}$.

Table 2--Computed values of A

Height	A
cm	
10	0.13
20	0.21
30	0.29
40	0.40
50	0.47
100	0.96

Taking $\rho = 0.0012$ g/cm^3 for air and $\beta = 1/\theta = 1/60$ sec^{-1}, we get $\sqrt{\rho\beta/A} = 6.3 \times 10^{-3}$ cm^{-1}. Therefore, the relaxation height $h = \sqrt{A/\rho\beta} =$ 160 cm and the 'half value' height = 0.693 × 160 = 110 cm. This means that we can expect that one-half of the ions formed in the first ten cm above ground are still present at 110 cm above ground.

In order to evaluate the constant of integration in (2), we assume that turbulence is sufficient to prevent appreciable recombination in the lowest ten cm. Then the flux of ions from the top of this layer is equal to the production of ions within the layer. A representative value for this quantity was found to be 139 ions of each sign per square centimeter per second. Now if we measure all heights from the ten-cm level, this should be equal to $S(0)$, that is, the flux of ions due to eddy diffusion at a height of ten cm above the ground. This is $S(0) = -A(ds/dh) = A s_o \sqrt{(\rho\beta/A)}$, which gives the value $s_o = 4.46 \times 10^4$ ions per gram (of each sign). This amounts to 53 ions of each sign per cubic centimeter at the ten-cm height, and half this number 110 cm higher, that is, 120 cm above ground. At a height of one meter, the figure would be 30 ions of each sign per cubic centimeter.

More strictly, one should take into account the variability with height of the coefficient of eddy diffusion A before integrating the differential (1). Thus it becomes $A(1)\,h^{6/7}\,(d^2s/dh^2) = \beta\rho s$ and integrate between $h = 10$ and 100 cm. From this

$$(d^2s/dh^2) = [\beta\rho/A(1)\,h^{6/7}]\;s \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where both s and h are variables. For our present purpose, however, it will suffice to take for the term $A(1)\,h^{6/7}$ an average, as shown above.

If we take for the first 100 cm above the ground a constant value of A four times as great (2 cm^{-1} g sec^{-1}) which is perhaps better for daytime conditions, 75 pct of the ions entering from below remain at the 100-cm level, while with $A = 0.5$ cm^{-1} g sec^{-1} only about 50 pct remain.

Conclusion--We see that the contribution of small ions produced by alpha particles near the ground to the total ion content at 100 cm from the ground (about 200-600 small ions per cm^3) is, in general, rather small, about five to ten per cent. In our estimate, we assumed that the mean coefficient A of eddy diffusion between 10 and 100 cm above ground is 0.5 cm^{-1} g sec^{-1}. The result, however, does not depend critically on the value of A chosen. Therefore, taking a constant value of A is not likely to introduce an appreciable error in the result.

Acknowledgment--The research reported in this paper was sponsored in part by the Geophysics Research Directorate of the Air Force Cambridge Research Center, Air Research and Development Command, under Contract No. AF19(122)-409.

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Fordham University,
New York, New York

(Manuscript received April 26, 1954; presented at the Thirty-Fifth Annual Meeting, Washington, D. C., May 3, 1954; open for formal discussion until May 1, 1955.)

Transactions, American Geophysical Union Volume 35, Number 6 December 1954

STUDIES OF THE ELECTRIC POTENTIAL BETWEEN KEY WEST, FLORIDA, AND HAVANA, CUBA

Gunther K. Wertheim

(Contribution No. 679 of the Woods Hole Oceanographic Institution)

Abstract--The mass transport of the Florida Current across the Key West-Havana section has been studied by means of the associated electrical potential due to the geomagnetic field. An analysis of the seasonal, daily, and short-term variations of the transport is presented, as well as a critical discussion of the limitations of the method of measurement employed.

Introduction

Motion of an electrolyte in the geomagnetic field leads to the development of an induced potential difference at right angles to the direction of motion. It has recently been pointed out [MALKUS and STERN, 1952] that the potential ϕ across a stream is related to the velocity v of the stream by

$$\int_0^d [\phi(\infty, d) - \phi(-\infty, d)]\, dz = \int_0^d \int_{-\infty}^{\infty} H_z v \, dx \, dz \quad \ldots\ldots\ldots\ldots \quad (1)$$

If the bottom is flat and nonconducting and the horizontal variation of the Earth's magnetic field is neglected, this reduces to

$$T = Vd/H_z \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where T = transport, m^3/sec; V = electrical potential difference, v; d = depth of water, m; and H_z = vertical component of the geomagnetic field, $webers/m^2$.

An analysis for an elliptical sea bed of finite conductivity [LONGUET-HIGGINS, 1949] shows that the effect of sea-bed conductivity is to reduce the potential between the edges of the stream by the factor

$$k = 1/[1 + (w/2d)(\sigma_B/\sigma_S)] \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where w = width of stream d = maximum depth, σ_B = electrical conductivity of bed, and σ_S = electrical conductivity of sea water. Application of (2) and (3) makes possible the continuous measurement of the net transport across any section of an ocean current, provided that the potential difference V across the section can be determined by establishing a suitable electrical connection across the stream. The kind cooperation of the Western Union Telegraph Company, which operates communication cables between Key West and Havana (Fig. 1), has made possible such measurements of the Florida Current during the past year.

The magnitude of the correction given by (3) may be estimated using, for the Florida Straits, the values $w = 160$ km, $d = 1.68$ km (maximum depth), $\sigma_B = 5 \times 10^{-5}$ mho/cm, and $\sigma_S = 5 \times 10^{-2}$ mho/cm to obtain $k \approx 0.95$.

Since the estimated correction for the effects of bottom conductivity is so small and its uncertainty so great, it was decided not to apply any systematic correction but to compute the transport directly from the measured potential by (2).

A further difficulty in relating transport to potential lies in the fact that (2) assumes a flat bottom. As long as the major portion of the Florida Current remains over the central portion of the Straits, the use of an effective average depth should be an acceptable approximation. If, however, owing to a meander, the axis should shift over the sloping bottom of the Key West side, erroneously high values of transport may result.

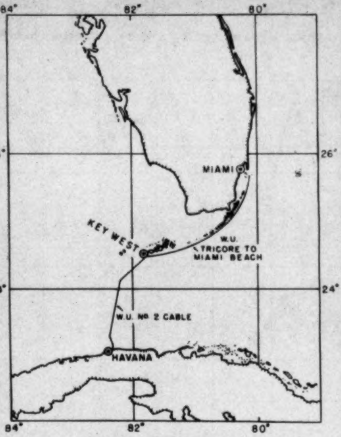

Fig. 1--Cable location

A numerical estimate of the magnitude of this effect was made using the velocity profile obtained by direct current measurements [PILLSBURY, 1887] and an average bottom profile. It was assumed that a shift of the axis of the current may be adequately represented by a rigid translation of the velocity profile. The results show that a meander of ten-km amplitude changes the potential by eight per cent, while a shift of 20 km changes the potential by 20 pct, a shift to the north serving to increase the potential. Little is known about the magnitude of the meanders that actually occur in this region so that the significance of this result cannot be evaluated at this time.

It should also be noted that it is possible to have a potential at right angles to the water motion even though there is no net transport across the section if the bottom is not level. Thus an elongated eddy running east over deep water and west over the shallower water close to Key West will indicate transport to the west even though there is no net transfer of water.

The data are obtained as a continuous curve of potential versus time. This curve exhibits fluctuations which may be divided into a number of categories according to their origin.

A 24-hr record will have the following characteristics: (a) It has an average value which is always positive and represents the average transport during the given interval. A study of the 24-hr averages gives a picture of the seasonal variation in the transport. (b) The data show variations having the tidal period which may be ascribed to the effect of the Atlantic and Gulf tides on the transport through the Florida Straits. (c) If the tidal variations are subtracted from the record, there remain irregular, short-term fluctuations which on some days are wholly absent and on others are greater in amplitude than either the tidal component or the average value. These fluctuations are found to be due to the variations in the horizontal component of the geomagnetic field. (d) Finally, there is noise of small amplitude and short duration which is ascribed to man-made interference. These various aspects of the record will be discussed in the following sections.

Average transport for the year 1952-1953

The average transport of the Florida Current obtained from (2) was 27×10^6 m^3/sec for the period August, 1952, to July, 1953. This figure lies well within previous estimates. Direct measurements with a current meter from an anchored ship [PILLSBURY, 1887] gave a transport of 28×10^6 m^3/sec. An estimate obtained from a series of dynamic sections [MONTGOMERY, 1941] yielded a transport of 26 to 30×10^6 m^3/sec. This agreement between the electrical measurements and previous estimates of transport confirms that the correction for bottom conductivity is small.

The seasonal variation of the transport

A curve of the seasonal variation of the transport of the Florida Current (Fig. 2) is based on 24-hr averages of transport to eliminate the tidal influence. The most striking feature of this curve is the wide range and rapid fluctuation of the transport. For example, early in December, 1952, the transport more than doubled in a period of only three weeks. The range of transport values during the year is almost as large as the average transport for the year, the lowest value being 14×10^6 and the highest 39×10^6 m^3/sec. These extreme values persisted for only a few days and are considerably outside the range of values previously reported for transport. It is interesting to note that WAGNER and CHEW [1953] have recently reported high values of transport computed from GEK data. These, however, appear to be partially due to tidal transports.

Comparison with tide-gage data--An independent measure of the variation of the current is available in terms of the average surface current which may be obtained from the difference in the tidal height at two stations on either side of the stream by the equation

$$\bar{v} = (h_1 - h_2)\, g/fy \qquad (4)$$

where f = Coriolis parameter, y = total distance across stream, and h_1 and h_2 = average height of sea surface above datum.

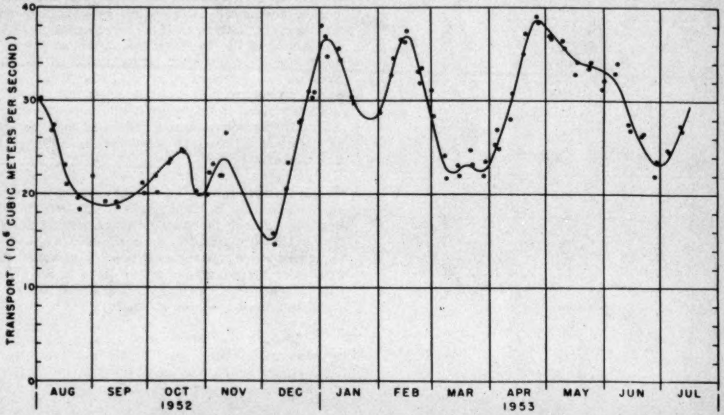

Fig. 2--Mass transport of the Florida Current

Figure 3a shows the transport for the year 1952-1953 as well as the difference between the Havana and Key West tide gages averaged over one-week intervals. Key West tide-gage data terminate in December, 1952, when this gage ceased operating. The qualitative agreement between the two curves is good, indicating that the surface current in the Straits of Florida is probably a good index of transport. Note that the rapid change in transport observed in December, 1952, is also observed on the tide-gage records and confirms the reality of the electrical observations. Corrections for atmospheric pressure and local wind effects have not been made.

Figure 3b shows a similar curve, comparing the electrically measured transport with changes in the slope of the sea surface between Bermuda and Charleston, which has been used as a measure of Gulf Stream transport. The agreement as to detail is poor, although there seems to be some general agreement on a large overall scale, leaving the way open for a number of possible explanations. It is possible that the surface current in the open ocean is determined more by local wind effects than by the overall motion of the water. In this case the average surface current (and hence the surface slope) no longer is a measure of transport. On the other hand, it is possible that the mass transport through the Bermuda-Charleston section is not proportional to the transport through the Key West-Havana section, the difference in transport being made up by the Antilles Current, or that the Charleston tide gage is affected by local piling up of water by the wind.

Correlation with the Atlantic wind system--According to a recent paper [MUNK, 1950], the transport of the Gulf Stream system is proportional to the curl of the wind stress over the Atlantic. Munk was able to obtain good agreement between the theoretical transport computed from the normal wind stress over the Atlantic and the known average value of transport. We now examine the correlation between monthly averages of wind and monthly averages of transport, and show there is no significant direct correlation over the interval for which data are available.

To obtain a measure of the wind stress curl over the Atlantic requires knowledge of the relation between wind stress and wind speed as well as information on the actual wind distribution. Neither of these can be accurately obtained. Moreover, even if the exact form of the wind-stress equation were known, it would not be possible to evaluate accurately the average wind stress from the average pressure maps unless the stress were a linear function of the speed. Instead of evaluating the average of the wind stress curl over a given area of the Atlantic, we may, as a suitable

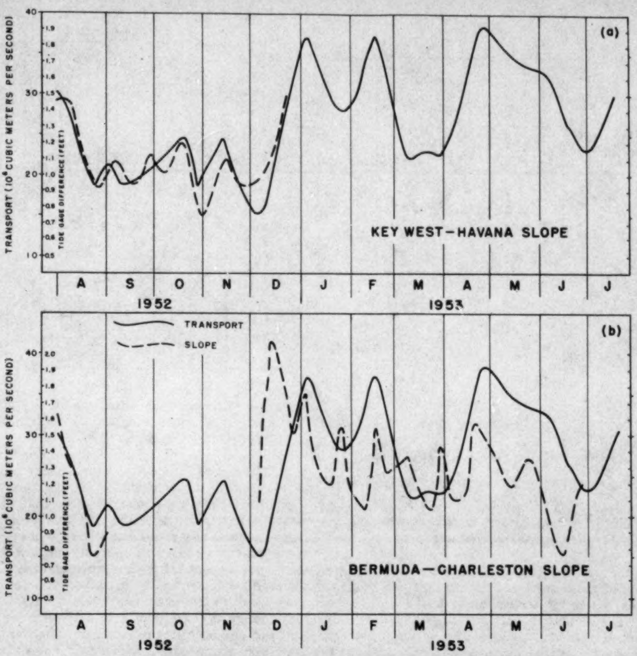

Fig. 3--Comparison of surface slope and transport (tide-gage differences are uncertain by an unknown additive amount)

equivalent use the circulation of the wind stress around a contour enclosing the same area. In view of the difficulty of obtaining the wind stress, we will investigate the use of the wind itself as the parameter for correlation.

The result of this analysis is shown in Figure 4. The units of the ordinates in these curves are arbitrary. The curve for trade-wind stress was obtained on the assumption that the drag coefficient is a constant and that the winds are relatively steady throughout the period over which the average was taken. The close resemblance which this curve bears to the other curves of trade-wind velocity and Atlantic wind circulation indicates that the choice of wind rather than wind stress for correlation with the transport is not a serious source of error, but will prevent the selection of one as the significant parameter.

Comparison of these curves with that of transport shown on the same figure indicates that there is no immediate good correlation between the variables in question. In order to obtain a quantitative measure of this preliminary conclusion, a correlogram was made for the wind circulation and transport for various months of phase shift between the two variables. The first positive correlation occurs with a -0.5-month phase lag, corresponding to a transport which leads the wind stress. It is assumed that this is a fortuitous correlation. Further positive correlations of the order of 0.5 are found at 6.5- and 18-month phase lag. It is apparent that no positive statement can be made about the relation between monthly average wind and transport on the basis of correlogram analysis, and it is quite possible that additional data will tend to lower the correlations obtained.

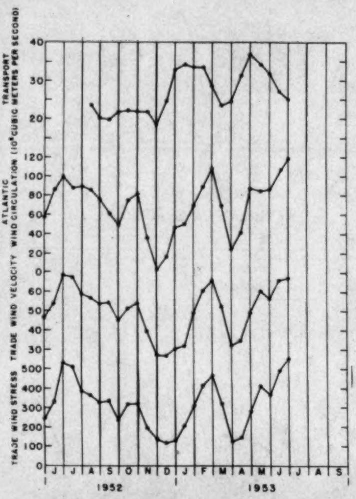

Fig. 4--Comparison of transport and the Atlantic wind system

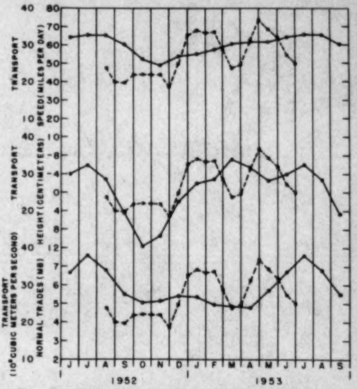

Fig. 5--Comparison of transport and normal curves of surface current, the Miami tide gage, and Atlantic wind circulation

There are, however, a number of serious objections to the analysis as here undertaken. Mathematically we cannot assume that the steady-state solution due to Munk will in any sense be applicable to the more rapidly changing regime here encountered. The method employed to reduce the weather map to a single significant number is not necessarily a reliable and sensitive means of measuring the significant changes in the wind circulation under all possible conditions. Further, it is intuitively clear that simultaneous changes in the wind strength along various portions of the contour will not produce a corresponding change in transport at the same time in the Straits of Florida. Phases should be introduced, but this can be accomplished only on the basis of some mathematical model which will suggest the required magnitudes. Moreover, the nearer segments may be more important. Finally, it must be pointed out that even on the basis of the most elementary mathematical model one cannot expect simple correlation between driving force and velocity (stress and transport).

As a test of the theory that the segments close to the Straits of Florida exert a dominant influence on the more rapid variations encountered within the seasonal curve, a comparison was made of the geostrophic wind off the coast of Florida and the southeastern Unites States with transport. The correlation obtained indicates that the flow through the straits may be predominantly controlled by the winds in this region; however, the data available are not sufficient to make a positive statement as to the significance of this result. In particular, it was noted that the rapid increase in transport observed in late December, 1952, does correspond to a complete reversal of the wind in the same period. The wind opposed the flow before, and aided the flow after, January 1, 1953. Reasonable correlation exists beyond that point.

Comparison with normal curves--Previous analyses of the factors contributing to the variations in the transport of the Gulf Stream have been carried out on the basis of 'normal' curves in the sense of month-by-month averages taken over many years. Figure 5 shows the normal curves of surface current in the Florida Straits [FUGLISTER, 1951], the height of the Miami tide gage, and the Atlantic wind circulation [CHASE, 1954]. On each there has been superposed the curve of monthly average transports (dotted). It has been considered significant in the past that the various normal curves show considerable similarity in shape. The 1952-1953 curve of transport which has been superposed shows large, relatively short-period variations about the normal curves while following their general trend. This is particularly noticeable in the case of the surface current which by previous argument appears to be a good index of transport. From the fact that these short-term variations

do not appear in the normal curves, it may be deduced that they are not regular annual phenomena but probably depend on essentially random effects, meteorological and otherwise.

Variations of tidal period

The relation between the lunar transit and variations in the transport was noted by PILLSBURY [1890]. The effect is thought to be produced in the following way.

Consider the Straits of Florida as a channel and the Atlantic and Gulf as two large reservoirs. The tide in the Atlantic (Miami) is semi-diurnal, the diurnal components being only ten per cent of the amplitude of the semi-diurnal ones. The tide in the Gulf is mainly diurnal, but there are times when the amplitude is greatly reduced and the appearance of the tidal record is essentially semi-diurnal.

The effect of the tidal oscillations in the Atlantic will be to send a long wave up the Florida Straits in a direction opposite to the flow of the Florida Current. This view is justified by the tidal differences tabulated for the various well-exposed points along the Florida Keys. High water arrives progressively later as one goes down the Keys toward Key West, the total difference between Miami and Key West being about two hours. This corresponds well to the time of propagation of a long tidal wave, computed from $\sqrt{gd}$, with $d = 650$ m. Such a wave, which is much longer than the depth of the channel in which it propagates, has maximum transport at maximum tidal height; that is, we expect a minimum in the transport at Key West two hours after high water at Miami. This simple expectation is not realized since it neglects the effect of the Gulf tide. However, to further substantiate the theory of the progressive tidal wave, we will compute the transport of such a wave at a time when the amplitude of the Gulf tide is at a minimum. This occurred on August 22, 1952, during the period when continuous data were obtained. Examination of the record shows a tidal transport amplitude of approximately 4×10^6 m^3/sec. On the other hand, the amplitude of the transport of a long wave is given by

$$T = Agh/v \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \quad (5)$$

Inserting the values for the Florida Straits

$A = 1.6 \times 10^8$ m^2 - Area of section
$h = 0.22$ m - Tidal amplitude
$v = 82$ m/sec - Velocity of tidal wave

we obtain approximately 4×10^6 m^3/sec, in good agreement with the measured amplitude.

Harmonic analysis--To obtain the harmonic components of tidal frequency found in the transport curve, Fourier analyses were made of various groups of 24-hr data, using midnight to midnight as the standard interval and employing a 24-ordinate scheme for the numerical analysis. The analysis was carried out to obtain the 24-, 12-, and 8-hr components using one-hour averages of transport as ordinates. The attenuating effect of such an averaging process on the amplitudes is only 0.05 pct. These components were subsequently separated into 12-, 12.4-, 24-, and 25.8-hr components by the use of a harmonic dial technique.

Table 1--Numerical results of harmonic analysis of transport data

Tidal component	Tidal period	Average amplitude of transport coefficient	Amplitude of tidal coefficient[a]			Coefficient of tide-producing force
			Miami	Key West	Galveston	
	hr	10^6 m^3/sec	ft	ft	ft	
M_2	12.42	3.8	1.20 ± 0.37	0.56 ± 0.11	0.31 ± 0.08	0.45 ± 0.09
S_2	12.00	1.6	0.24 ± 0.06	0.17 ± 0.04	0.10 ± 0.01	0.21 ± 0.06
K_1	23.93	3.6	0.13 ± 0.04	0.29 ± 0.09	0.38 ± 0.10	0.27 ± 0.09
O_1	25.82	3.4	0.11	0.29	0.36	0.19

[a] The tolerances given for the tidal coefficients represent the effect of smaller coefficients of only slightly different period which could not be separated in the analysis of transport.

The results of the harmonic analysis are shown in Table 1, together with the coefficients of the tide-producing forces, and the tidal harmonics at Key West, Miami, and Galveston Bay. It should be noted that the harmonic components obtained by the analysis of transport are in a ratio which is between those of the semi-diurnal Atlantic tide (Miami) and the diurnal Gulf tide (Galveston), confirming the dependence of the transport on both tidal systems.

Comparison with tide data--A solution to the hydrodynamical problem of the Florida Straits-Atlantic-Gulf of Mexico system which is useful in interpreting currents in the Florida Straits has not been obtained. A complete solution must take into account Coriolis force, stratification of the water, and slope of the sea bottom. In order to test the idea that both Atlantic and Gulf tides play a significant role in the diurnal variation of the transport, we have combined the tidal harmonics of the Miami and Tampico tide stations with suitable phases so as to give the simultaneous effects at the Key West-Havana section. The result of this rather arbitrary procedure, together with a curve of transport for August, 1952, is shown in Figure 6. There has been no attempt to weight the two tidal components. The curve is simply a linear combination of existing tidal amplitudes. The Miami tide, representative of the Atlantic, is displaced by two hours and inverted to represent the time of travel of the long wave up the Florida channel. The Tampico tide is displaced by six hours for similar reasons.

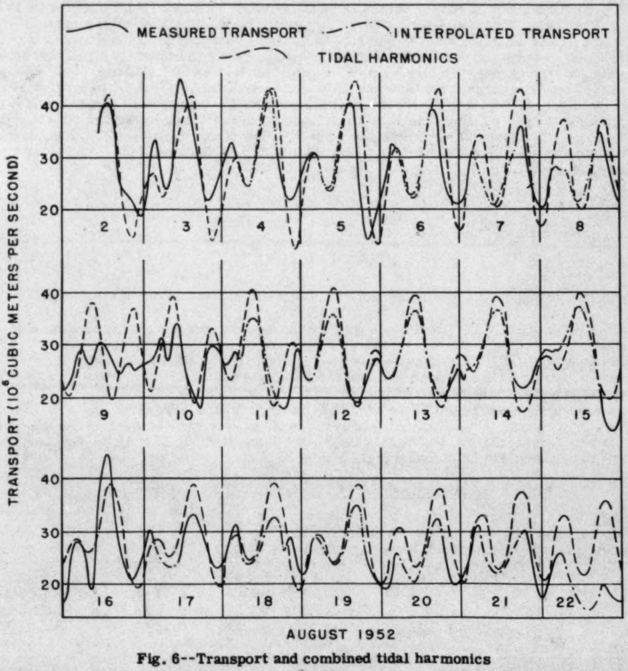

Fig. 6--Transport and combined tidal harmonics

The resulting agreement is good, except in those regions where the amplitudes of the tidal transport are small. Here other influences, such as local winds, may be significant. It is thought that this agreement may be taken to indicate that the above explanation of the tidal dependence of the transport is essentially correct in so far as it points out the two pertinent parameters. No further significance should be attached to the linear combination of tidal components of the two stations employed.

Irregular fluctuations and short-term noise

Geomagnetic noise--In addition to the components discussed above, the records also contain fluctuations of unpredictable amplitude and duration. The amplitude of these fluctuations is usually within a given range for as long as six hours but varies rapidly from day to day. These fluctuations are due to ionospheric or geomagnetic disturbances which produce Earth currents whose disturbing influence has long been recognized by the wire-communications engineer. The largest amplitude recorded during the year was approximately 1.5 v over a distance of 162 km, or ten mv/km. Potential gradients larger by a factor of 10^3 have been reported on long-line communication cables during severe geomagnetic disturbances in years of sunspot maxima.

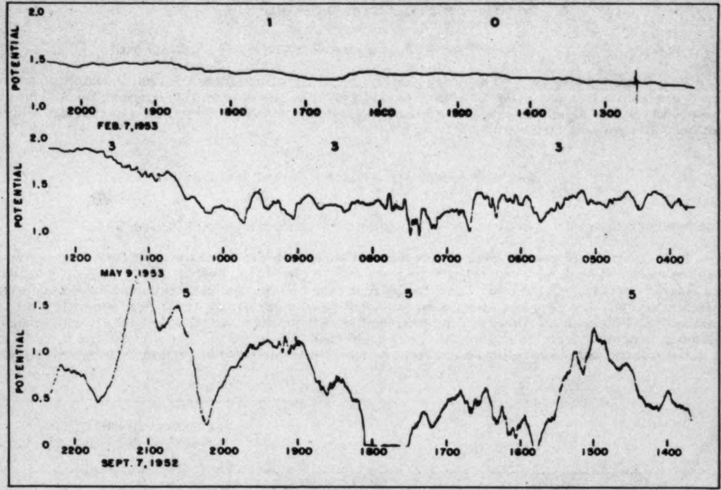

Fig. 7--The effect of geomagnetic disturbance on the electric potential

Figure 7 shows three sample records selected to show the range of geomagnetic effect encountered during the year. The numbers shown along the top edge of each record are the Cheltenham K indices, which are measures of the intensity of the disturbance of the geomagnetic field during consecutive three-hour periods. The correspondence between high K index and record noise was consistently observed throughout the year. The large majority of records obtained resembles the middle sample corresponding to a K index of 3. Long periods with index O are rare, and the one shown is the quietest record obtained.

Elementary electromagnetic theory indicates that the voltage measured in the loop consisting of the cable and the water above it may be related to the time rate of change of the component of the geomagnetic field normal to the plane of the loop. It should be noted that whereas the emf due to water motion is independent of the location of the cable, the geomagnetically induced emf depends on the vertical area of the cross section above the cable.

It follows directly from the law of induction that

$$E = -\mu A\,(\partial/\partial t)\,[H(t)\cos\Phi(t)] \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

where E is the induced emf, A the area of the section, H the average horizontal component of the field, and Φ the angle between the normal to the section and the direction of H. Examination of a magnetogram indicates that the required time derivative of the term $H\cos\Phi$ cannot be obtained accurately by numerical means. As an alternative, however, we may compare the integrated voltage with the magnetic field itself. Integrating (6) with respect to time yields

$$\int_0^t E\,dt = \mu A\,[H(o)\cos\Phi(o) - H(t)\cos\Phi(t)] \quad (7)$$

This expression may now be expanded in terms of the time average values of H and Φ, $\overline{H}$ and $\overline{\Phi}$, and their time dependent perturbations h(t) and $\phi(t)$ to obtain

$$\int_0^t E\,dt = \mu A\,[H(o)\cos\Phi(o) - \overline{H}\cos\overline{\Phi}\cos\phi(t) + h(t)\sin\overline{\Phi}\sin\phi(t) - h(t)\cos\overline{\Phi}\cos\phi(t) + \overline{H}\sin\overline{\Phi}\sin\phi(t)] \quad (8)$$

The first term depends only on the lower limit of the integration and is constant in time; the second term is essentially constant in time since $\phi(t)$ is small; the third term is negligible since it involves the product of two small factors. This leaves the last two terms as the major time-variant contributions. Recognizing that $\cos\phi(t) \approx 1$, we obtain

$$\int_0^t E\,dt = \mu A\,[\text{const} - h(t)\cos\overline{\Phi} + \overline{H}\sin\overline{\Phi}\sin\phi(t)] \quad (9)$$

These terms express respectively the contributions of the fluctuations of H and D.

This equation will now be used to compare the noise with the fluctuations of the geomagnetic field as recorded by the closest magnetic observatory in San Juan, Puerto Rico. We have selected the magnetograms for September 7 and 28, 1952, for the comparison because these days were magnetically active. The required integration was performed numerically by 20-min intervals after subtraction of the average value and the principal tidal component of transport. The result of this integration together with the evaluation of the right-hand side of (9) are given in Figure 8. It should be noted that the agreement with respect to fine detail is limited by the 20-min interval chosen for

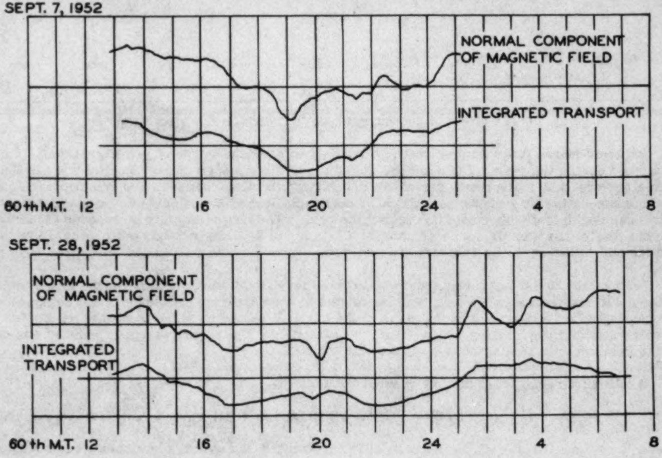

Fig. 8--Comparison of integrated transport with geomagnetic field the integration and by the physical separation of the cable site and the magnetic observatory. However, the agreement demonstrated does indicate that the noise observed on days having a high Cheltenham K index may be ascribed to the variations in the magnitude and direction of the horizontal component of the field. (Note that the transport is measured in terms of the vertical component of the field whose fluctuations produce only a second-order effect.)

Atmospheric noise--It was also noted that electrical disturbances in the atmosphere, lightning, and so forth, will affect the record. The usual appearance of the record during times of electrical storms is characterized by short vertical lines apparently due to single electrical discharges. Since the duration of these pulses is short, it is not possible to obtain an estimate of the magnitude of the voltages involved.

Instrumentation

The essential details of the instrumental setup are shown in Figure 9. The apparatus consists of two electrodes placed in the sea, one on each edge of the stream connected through an overload cut-off and an attenuating pad to a recording potentiometer.

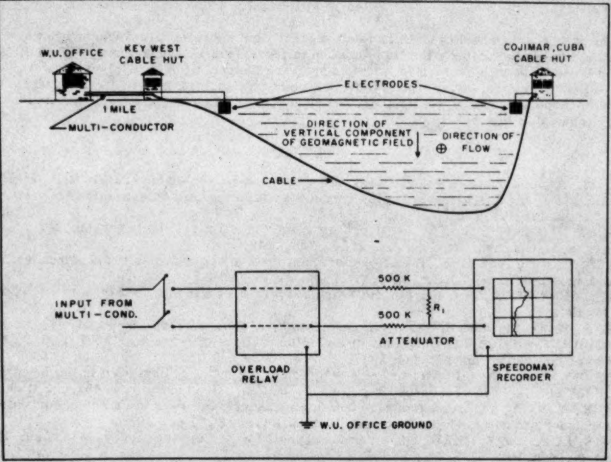
W.U. OFFICE
KEY WEST CABLE HUT
COJIMAR, CUBA CABLE HUT
ELECTRODES
1 MILE
MULTI-CONDUCTOR
DIRECTION OF VERTICAL COMPONENT OF GEOMAGNETIC FIELD
DIRECTION OF FLOW
CABLE
INPUT FROM MULTI-COND.
500 K
R_1
500 K
ATTENUATOR
OVERLOAD RELAY
SPEEDOMAX RECORDER
W.U. OFFICE GROUND

Fig. 9--Recording setup

The electrodes consist of 18 sets of specially matched GEK electrodes [VON ARX, 1950] connected to the recording equipment by the Western Union no. 2 cable whose parameters are

Copper resistance	990 ohms
Dielectric resistance	2.06 megohms

The effective load impedance at Key West is one megohm while the average recorded voltage is approximately one volt. Using these values and the cable parameters, it may be shown that no correction need be made for cable losses, the error being less than 0.1 pct which is less than the errors inherent in the recording and reading process.

During August, 1952, Key West-Havana data were obtained daily from 17h 00m until 06h 30m and on weekends from 17h 00m Friday until 06h 30m Monday, as well as on holidays. The daily recording program was abandoned at the end of August and only continuous weekend recording retained.

Conclusion

It has been shown that the cross-stream potential is a good measure of transport in the case of the Florida Straits. The major disturbing factor is the activity of the geomagnetic field which under most conditions prevents correlation of the instantaneous transport with the instantaneous voltage. Further uncertainty is introduced by the effects of bottom conductivity and the sloping sea bed. However, these effects are estimated to be small.

Summary--The geomagnetic disturbance has been successfully related to the horizontal component of the Earth's field. The validity of the surface slope as an index of transport in the Florida Straits has been confirmed. The tidal modulation of the transport has been shown to depend on both the Atlantic and Gulf tides. An analysis of the relation between the Atlantic wind system and the seasonal variation of the transport of the Gulf Stream has failed to yield positive results, and calls for a more sophisticated mathematical approach.

The program of measurements has been extended for one additional year with a view toward further investigation of the seasonal variation of the transport and other open questions.

Acknowledgments

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RELATIVE SIGNIFICANCE OF THE DIFFERENT METHODS OF MODERN GEODESY

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Abstract--In geodesy, several methods will be applied for solving the crucial problems of geodesy: (1) determination of the dimensions of the reference ellipsoid, (2) the shape of the geoid, and (3) the computation of the geodetic control points. Therefore, the possibilities, limitations, and relative significance of the different methods used or planned to be used in geodesy, such as classic, flare, and rocket-star triangulation; arc-measuring, Shoran and Hiran, the solar eclipse, occultation, and Moon photographing (Markowitz) methods, as well as the gravimetric method, will be discussed.

Introduction--In order to be able to compute adequate coordinates for mapping and charting control points, we need to know the size and shape of the Earth. This most important problem of geodesy will be solved in two phases. First, we determine the size and shape of a reference ellipsoid, that is, the equator radius a and the flattening α of the meridian of this ellipsoid. Second, we have to compute the distances and tilting between the reference ellipsoid and the geoid at required points. These quantities, the distance N of the geoid, and the deflection of the vertical components ξ and η will give the detailed shape of the geoid. This surface is very important because it is the equipotential level to which the observations will be referred.

It is true that we cannot use the geoid for geodetic computations because it is too complicated, but we need to know its distance from the ellipsoid and its tilting against the ellipsoid in order to convert our measurements from the geoid to the ellipsoid.

For measuring the dimensions of the reference ellipsoid, we need geodetic yardsticks, that is, accurately measured arcs in different parts of the world. This is the geodetic part of this principal geodetic problem. These yardsticks have been measured until the present time almost exclusively by the aid of the classic triangulation. This method gives us arcs along the continents. Yardsticks across the narrow waters can be obtained by the flare triangulation or by Shoran measurements, which have been developed and used only recently. The Shoran method seems to be particularly promising; its only drawback is that it is rather expensive.

As the classic triangulation method is well known, the flare triangulation method is not too important, and the Shoran method is adequately discussed elsewhere, I will not go into these methods in detail.

Celestial triangulation--To stretch the geodetic yardsticks across the oceans, we have to use celestial triangulation. There exist three types of celestial triangulation which all use the Moon as one triangulation point. These methods are the solar eclipse method, the star occultation method, and the Moon position camera or Markowitz method.

All of these methods will give yardsticks for geodetic purposes. The Markowitz method seems to be promising because it enables accurate Moon observations at different parts of the world very often, and it does not depend on the rare eclipses or relatively rare star occultations. Therefore, I would like to congratulate Markowitz and hope that his method will be put in practice on an international scale as soon as possible.

Celestial triangulation cannot, however, yield absolute yardsticks. Its accuracy is dependent on the distance of the Moon (Moon's parallax) and, therefore, on the radius a of the Earth's equator. An error in a will affect with full weight the accuracy of the yardsticks obtained. Only in one way can we escape this error.

If we carry out solar eclipse observations at two points A and B, the distance between which has been or will be measured by triangulation, we can use this known distance to compute the Moon's distance and so get the distance across the ocean without using the equatorial radius. The accuracy of this transoceanic yardstick is, of course, dependent on the accuracy of the distance AB.

This is the reason why one solar eclipse expedition has been sent to Iran to photograph the solar eclipse of June 30, 1954. The observations in Iran and Scandinavia will, it is hoped, provide the base line AB; and the observations in Labrador and Scandinavia, the distance across the Atlantic.

There is still another celestial method, the rocket-star triangulation, which was invented and developed by the Finnish geodesist and astronomer, Y. Väisälä, a decade ago. His idea is to photograph simultaneously from several observation points a rocket and the neighboring stars. By measuring the small angular distances between the images of the stars and the rocket, the direction of the rocket from the observation points can be accurately computed. If the rockets can be shot to an elevation of several hundred kilometers, this method would give the distance even across the oceans. Needless to say, we can use this method also for triangulation along the continents. Its advantage is that we can observe very large triangles, but so far this method has not been put into practice.

How can we use these yardsticks measured along the continents or across the oceans in order to get the radius a of the equator and the flattening α of the meridian? We must fix them exactly in their proper places on the Earth. In other words, we have to solve the astronomical problem of finding the central angle corresponding to these arcs. This is easier to say than to do. The astronomical observations which refer to the irregular geoid should be converted from the geoid to the ellipsoid, so we must compute gravimetrically the deflections of the vertical at these points. If, for instance, we want to use the distance to be measured between Labrador and Scandinavia during the solar eclipse of June 30, 1954, we need to know the absolute deflection of the vertical at the observation points in Labrador and Scandinavia. If we do not determine the deflections of the vertical, we can arrive at quite erroneous results. Figure 1 shows this very clearly.

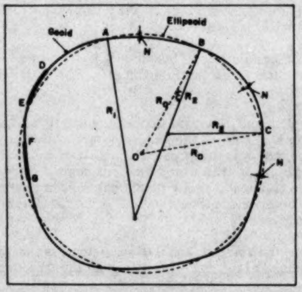

Fig. 1--The irregular geoid and its effect upon the radii of curvature; because of the undulations N of the geoid, we get the wrong dimensions for the Earth's ellipsoid; arc AB gives too large a radius R_1 and arc BC too small a radius R_2, while the correct value is R_0; even if we smooth the undulations by the isostatic reductions, the unknown subsurface masses bring about similar errors; the measured arc DE gives too small a radius and arc FG too large a radius

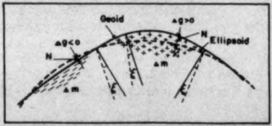

Fig. 2--The interrelation of mass and gravity anomalies, geoid undulations, and deflections of the vertical; the mass anomalies Δm (surpluses or deficiencies) bring about the gravity anomalies Δg, undulation N of the geoid, and deflection of the vertical ξ; Δg can be observed and N and ξ (and η) can be computed; this is the fundamental idea of physical geodesy

Suppose that the measured arc AB is in an area of mass deficiency where the geoid is below the reference ellipsoid and that the arc BC is in an area of excess mass where the geoid is above the ellipsoid. In such a case, when we compute the radius of the curvature of the ellipsoid R, we will get too large a value R_1 from the arc AB, and from the arc BC the value R_2 will be too small. Even if we try by the aid of isostatic reductions to eliminate the effect of the topography, the unknown subsurface masses will still introduce similar, although usually smaller, errors.

Figure 2 shows that the mass anomalies Δm bring about the quantities Δg, N, and ξ (as well as η) and explains the fundamental idea of the world-wide gravity program.

As the absolute deflection of the vertical components have hitherto been obtained only by the aid of gravity anomalies, I would particularly emphasize the global significance of the gravimetric method. The combination of the measured arcs and the gravimetric method will give better results than the measured arcs alone.

Until now, we have used the condition equation $\Sigma(\xi^2 + \eta^2) = \min$ in computing the dimensions of the reference ellipsoid. We have known that this method is not correct because there are areas, for instance, Europe, where the $\Sigma(\xi^2 + \eta^2)$ cannot be a minimum. In fact, both components of the deflection of the vertical in Europe are systematically positive. This fact will, of course, not lead to good results. Only in the case that the measured arcs span very long distances will the error brought about by this fact be smaller.

Gravimetric method--In order to eliminate the effect of deflections of the vertical, we have only to make accurate astronomical observations close to the end points of the measured arcs and, in addition, to carry out local gravity surveys in the neighboring areas so that we can, in connection with the already existing general gravity survey, compute gravimetrically the deflection of the vertical components ξ_g and η_g. If we use these for the initial station and compute on the assumed reference ellipsoid the coordinates of the other end of the arc, we will get geodetic-astronomical deflection of the vertical components ξ and η. We will have, therefore, at the end point of the arc two sets of deflections of the vertical components ξ and η, which refer to the reference ellipsoid used; and ξ_g and η_g, which are mostly independent of it. Now if the differences $(\xi - \xi_g)$ and $(\eta - \eta_g)$ are small, then the assumed reference ellipsoid is good. If they are large, that is, ten seconds, then we have to correct the dimensions of the reference ellipsoid until these differences are as small as possible. In this simple way every measured arc either along the continent or across the oceans will give corrections to the dimensions of the used reference ellipsoid. Together they will give us the most plausible values for the Earth's dimensions.

The quantities a and α can be checked rather well now, with existing yardsticks. Of course, the accuracy will rise if additional arcs are measured.

The second important problem is to convert the existing geodetic systems to one world geodetic system, which can be done by computing gravimetrically the undulation N of the geoid and the deflection of the vertical components ξ and η at the initial points of the different geodetic systems. All we need is a good local gravity survey in the neighborhood of the initial point and a general gravity station net farther from the computation point. The Stokes formula will give the quantity N, and the Vening Meinesz formulas will give the quantities ξ and η.

As the difficulties of the gravimetric method have frequently been over-estimated, I would particularly point out that the gravity anomaly field far from the computation point will have only a small effect, especially on the computation of the deflection of the vertical components. Therefore, we can, while additional observations are being carried out, compute ξ_g and η_g relatively accurately with the existing gravity material. In many places also, we can compute N with an accuracy of some few meters. There are many points now where the error of ξ_g and η_g is not larger than one second. Very large areas exist where this error will be less than three seconds. Needless to say, it is possible to compute the quantities N, ξ_g, and η_g at any needed points in the neighborhood of which good gravity station nets exist. This is the case in the Northern Hemisphere. In the Southern Hemisphere, we need to carry out a general gravity survey, particularly at sea.

There exist two different methods for gravity measurements at sea. First, we can use the underwater gravity meters to survey the shallow shelf areas up to 200-m depths. Such measurements will enlarge the known gravity field on a rather big scale at the edges of the continents. Then we have the Vening Meinesz method for gravity surveys from submarines.

This method (by now classical), as used by Vening Meinesz and American investigators, has enabled about two to six stations to be measured in a day and with an accuracy, according to several studies, of from three to five milligals.

Small-scale mapping--Another important fact is that current practice has been to compute deflections of the vertical astro-geodetically according to the formulas

$$\left.\begin{array}{l} \xi = \phi' - \phi \\ \eta = (\lambda' - \lambda)\cos\phi \qquad \text{or} \\ \eta = (A' - A)\cot\phi \end{array}\right\} \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where ϕ', λ', and A' are the astronomical coordinates; and ϕ, λ, and A are the geodetic coordinates. If we invert these formulas obtaining

$$\left.\begin{array}{l} \phi = \phi' - \xi_g \\ \lambda = \lambda' - \eta_g \sec\phi \\ A = A' - \eta_g \tan\phi \end{array}\right\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

we get an excellent method for fixing control points without triangulation. We compute only the gravimetric deflections of the vertical components ξ_g and η_g and convert, by their aid, the astronomical coordinates from the geoid to the ellipsoid. The accuracy of this method, presuming that the astronomical measurements are reliable, is of the order of one to three seconds. The accuracy of one second is sufficient for all maps of smaller scale than 1:100,000, and the three-second accuracy for maps on scales smaller than 1:250,000.

This method can, of course, be combined with the local triangulation. In the developed areas where large scale maps are needed, we have to carry out local triangulations. In order to put these areas on the same system even though separated by vast undeveloped areas, such as deserts and mountain ranges, we make astronomical observations at one point, at least, of every local triangulation, as well as making adequate gravity surveys in their neighborhoods. We then compute the gravimetric deflections of the vertical and, using (2), the geodetic coordinates ϕ, λ, and A. I cannot emphasize too much the practical significance of this method.

Until now, the components ξ and η have been computed at triangulation points which are often on mountains and hilltops. Because of the rough topography, this procedure is rather complicated and time wasting. Instead, we can make astronomical observations in the neighboring level lands, still better if the gravity field there is as smooth as possible. Then we join this point by a triangle or by traverse to the triangulation point so that the coordinates ϕ, λ, and A can be observed at this level land point gravimetrically as well as astro-geodetically.

Conclusion--Leaving out several minor points, the gravimetric method, either alone or in conjunction with already existing measured arcs and additional astronomical observations, can yield:

(1) The checking of the dimensions of the reference ellipsoid as well as the constants of the international gravity formula. (In my opinion, neither the dimensions of the international ellipsoid nor the constants of the international gravity formula needs very large corrections.)

(2) The absolute deflections of the vertical at the initial points of geodetic systems and the conversion of the existing systems to a world geodetic system.

(3) A good method for obtaining control points without triangulation in such areas where maps on scales of 1:100,000 or smaller are sufficient.

(4) The undulation of the geoid and the deflection of the vertical at any needed point.

This is in fact the 'summa geodaesiae.' It is in our hands to solve these problems, and they will be solved soon. The best evidence for that is the vital interest of most countries in gravity surveys and in the gravimetric method.

Needless to say, all gravity surveys must be connected to the same system. In that respect, Woollard's group deserves the highest credit; while in gravity measurements at sea, Vening Meinesz and the Columbia University group under the leadership of Ewing and Worzel have done the essential part.

Acknowledgment--I am particularly grateful to the Directorate of the Air Force Cambridge Research Center, whose support has enabled the Columbus group to carry out world-wide gravity studies.

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WAVE, LONGSHORE CURRENT, AND BEACH PROFILE RECORDS FOR SANTA MARGARITA RIVER BEACH, OCEANSIDE, CALIFORNIA, 1949

R. L. Wiegel, D. A. Patrick, and H. L. Kimberley

__Abstract__--The results of ten months of measurements of waves, longshore currents, and beach conditions for Santa Margarita River Beach are presented. Tables and graphs give the height, period, and steepness of the incident waves as measured by a subsurface, differential-type pressure recorder; breaker heights as computed from these data; observed wave directions; longshore current measurements, both magnitude and direction, as obtained by tracing dye thrown into the water; and beach profiles measured along three ranges 500 ft apart from the berm to a depth of about 25 ft. It was found that the three sets of profiles were not consistent in regard to their relationship with varying wave conditions, and further that the type of beach profile (storm or ordinary) apparently did not bear the same relationship to the wave steepness as has been found in laboratory studies.

__Introduction__--In the course of an oceanographic study by the University of California in conjunction with the U. S. Marine Corps, measurements and observations were made of waves, longshore currents, and beach conditions in the vicinity of the Santa Margarita River at Oceanside, California (Fig. 1). These data, covering a period of ten months, are presented for the purpose of making available to the oceanographer and geologist a type of field information which is almost non-existent. To the authors' knowledge the only other published study of this type which presents data collected over a relatively long interval was made alongside the pier of the Scripps Institution of Oceanography [SHEPARD and LaFOND, 1940].

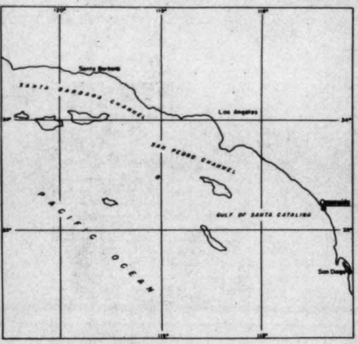


Fig. 1--Pacific Ocean in the vicinity of the Santa Margarita River Beach, Oceanside, California

__Wave records__--A thermopile wave meter [ISAACS and WIEGEL, 1950] was used as the underwater pressure pickup unit. It consisted of a synthetic rubber bellows mounted on a plastic base with an encased thermopile. The hot junctions of the thermopile were in contact with the air in the bellows, while the cold junctions, insulated from the air chamber in the bellows, were in thermal contact with the surrounding sea water. The pickup unit, located approximately 4200 ft offshore about 43 ft below MLLW, was connected by cable to a commercial recording self-balancing potentiometer ashore.

In addition to the automatically recorded wave characteristics, obtained for two weeks in March, 1949, and then almost continuously from May through the middle of January, 1950, observations were made of the angle the breakers made with the beach, thus giving a fair indication of the wave direction. Because of the location of Santa Margarita River Beach, about the only waves of any significance come from a small sector due west, or from a southerly direction, with the exception of those from near-coastal storms [TODD and WIEGEL, 1952].

The records, analyzed for a 20- to 30-min interval every eight hours, are presented in Figure 2. The primary data are the average wave period and the 'unrefracted' deep-water height of the highest one-third of the waves, the so-called 'significant waves.' The term 'unrefracted' wave height refers to the height the waves would have had in deep water if unaffected by refraction, and it is related to the height in transitional water [WIEGEL, 1953] by the equation [U. S. NAVY HYDROGRAPHIC OFFICE, 1944; WIEGEL, 1948]

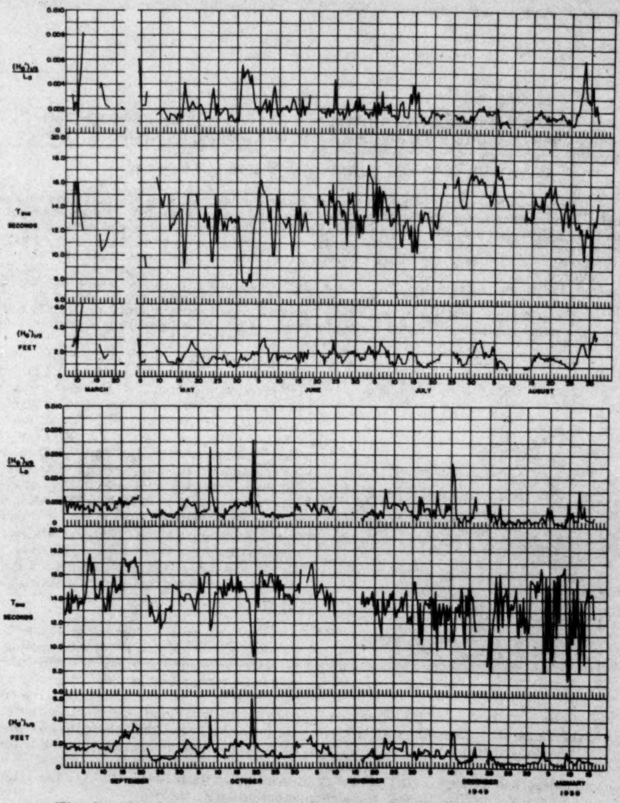


Fig. 2--'Unrefracted' deep-water wave height, period, and steepness, Santa Margarita River Beach, Oceanside, California

$$H_0' = H/\sqrt{C_0/2nC} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where

$$n = (1/2)\left[1 + \frac{4\pi d/L}{\sinh(4\pi d/L)}\right]$$

$C_0/C = 1/\tanh(2\pi d/L)$
H = wave height at location of wave meter
H_0' = unrefracted deep-water wave height
C = wave velocity
C_0 = deep-water wave velocity
L = wave length
d = water depth

The wave steepness also is presented in Figure 2, as laboratory studies have indicated that it is this wave characteristic which is most closely related to the phenomenon of changes in the beach profile and the movement of sand onto and off of beaches [BEACH EROSION BOARD, 1936; JOHNSON, 1949; SAVILLE, 1950]. The steepness is the ratio of the unrefracted deep-water wave height to the deep-water wave length, H'_0/L_0, where the deep-water wave length is given by the equation

$$L_0 = gT^2/2\pi \qquad (2)$$

where

L_0 = deep-water wave length
g = acceleration of gravity
T = wave period

In Figure 3, data on breaker conditions are presented. The directions are visual observations, made almost daily, excepting weekends. Data for both primary and secondary trains (if present) are shown. It is emphasized that the breaker direction is not necessarily the same as the deep-water wave direction owing to the effect of refraction (see sketch at the bottom of Fig. 3). With the exception of the visual observations presented for the month of April, the breaker heights were computed from the records of the Thermopile Wave Meter with the use of empirical curves [U. S. NAVY HYDROGRAPHIC OFFICE, 1944]. Subsequent laboratory studies have shown, however, that the breaker height depends upon the beach slope as well as the wave characteristics; however, for the slope of the beach under discussion (about 1/30), the original empirical data are effectively the same as the latest published data [IVERSEN, 1952].

Table 1--Measured and observed wave and longshore current characteristics

Item		1949										1950
Symbol and units	Range	Mar. 8-22	Mar. 28-Apr. 30	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Jan. 1-16
$(H'_0)_{1/3}$ (feet)	0-2	40	..	77	64	69	85	76	87	89	97	93
	2-4	50	..	23	36	31	15	24	13	11	3	7
	4-6	10	..	0	0	0	0	0	0	0	0	0
T (average) (seconds)	<9	0	24	7	7	0	0	0	0	0	7	19
	9-11	29	12	19	7	3	7	0	3	0	14	25
	11-13	29	4	26	36	35	19	24	3	35	45	19
	13-15	21	40	44	46	38	55	45	55	50	31	19
	>15	21	20	4	4	24	19	31	39	15	3	18
$(H'_0)_{1/3}/L_0$	<0.001	0	..	4	0	3	11	14	19	22	61	69
	0.001-0.002	20	..	62	50	62	67	69	71	78	25	31
	0.002-0.003	30	..	18	36	24	11	17	6	0	7	0
	0.003-0.004	30	..	4	4	16	4	0	0	0	4	0
	0.004-0.005	10	..	4	10	0	4	0	0	0	3	0
	>0.005	10	..	8	0	0	4	0	4	0	0	0
$(H_B)_{1/3}$ (feet)	0-2	7	8	00	0	0	6	0	1	12	59	91
	2-4	29	76	80	69	64	74	69	74	69	38	9
	4-6	36	16	20	30	36	19	20	25	19	2	0
	6-8	21	0	0	1	0	1	11	0	0	1	0
	>8	7	0	0	0	0	0	0	0	0	0	0
Direction of primary breakers	WNW	..	4	0	0	0	0	0	0	..	..	..
	W	..	12	0	0	0	0	0	14	..	..	..
	WSW	..	39	28	35	0	0	0	43	..	..	..
	SW	..	5	67	61	89	93	100	43	..	..	..
	SSW	..	0	5	4	11	7	0	0	..	..	..
Littoral current magnitude (knots)	0-0.2	..	33	55	63	50	33	9	57	..	..	..
	0.2-0.4	..	33	18	25	33	45	18	29	..	..	..
	0.4-0.6	..	34	9	0	17	22	18	14	..	..	..
	0.6-0.8	..	0	9	17	0	0	27	0	..	..	..
	>0.8	..	0	9	0	0	0	27	0	..	..	..
Littoral current direction	N-S	..	83	42	27	7	10	45	75	..	..	..
	S-N	..	17	58	73	93	90	55	25	..	..	..

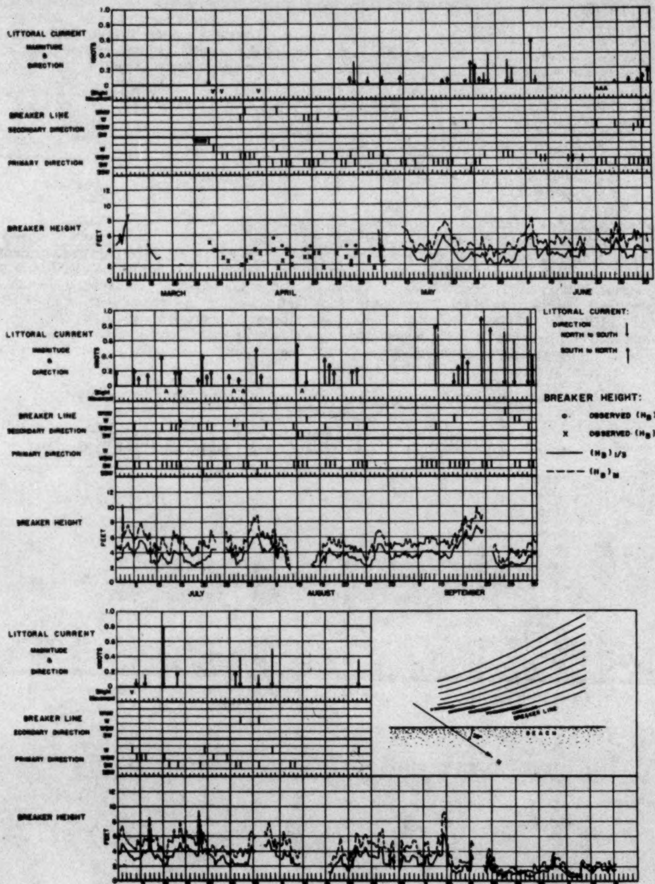


Fig. 3--Breaker height and direction, littoral current direction and magnitude, Santa Margarita River Beach, Oceanside, California

In Table 1 are presented the times that the deep-water wave heights, the average periods, the wave steepnesses, and the breaker heights and directions were within certain ranges of values. It can readily be seen that unrefracted deep-water heights were rarely above four feet and the breakers rarely above six feet. Most of the predominant waves (that is, the 'primary' trains) were from a southerly direction.

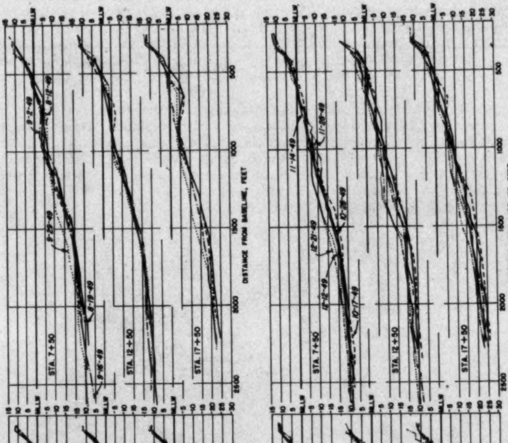


Fig. 4--Beach profiles, Santa Margarita River

Longshore currents--Observations of the longshore currents were made nearly every weekday during a large part of the time. This was done by throwing a small package of dye into the surf and measuring the distance the dyed water moved in one minute (about the maximum length of time the dye could be traced before it dispersed almost completely). The data on magnitude and direction are shown in Figure 3 and are presented in Table 1 as the time the measurements were within certain ranges of values. It can be seen that the direction of longshore movement generally corresponded to the direction of the primary trains of breakers. On a few occasions, however, the direction corresponded to the direction of the secondary train. This was because the magnitude of the longshore current depends directly upon the breaker height, but inversely with the period; thus, the short-period waves from the near-coastal storms were sometimes more important than the larger long-period waves coming from another direction, insofar as longshore currents are concerned [PUTNAM, MUNK, and TRAYLOR, 1949; INMAN and QUINN, 1951].

Beach conditions--The interaction of the ever-varying surf and the material of which a beach consists cause constantly changing beach conditions. In order to obtain data on this phenomenon, beach profiles were taken at about two-week intervals (Fig. 4). Range lines were established along the beach as shown in Figure 5; however, only ranges 7+50, 12+50, and 17+50 were used continuously. The method of obtaining profiles through the surf by means of a DUKW and leadline has been described elsewhere [PATRICK, 1952]. In addition, samples of sand were analyzed for mechanical size distribution and mineralogical content (Fig. 6).

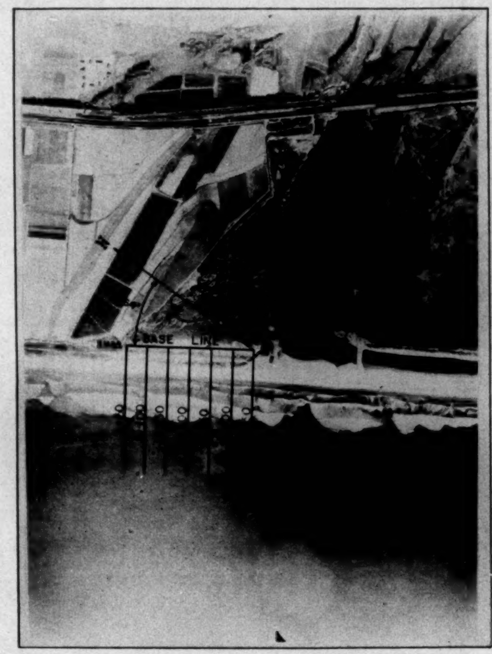
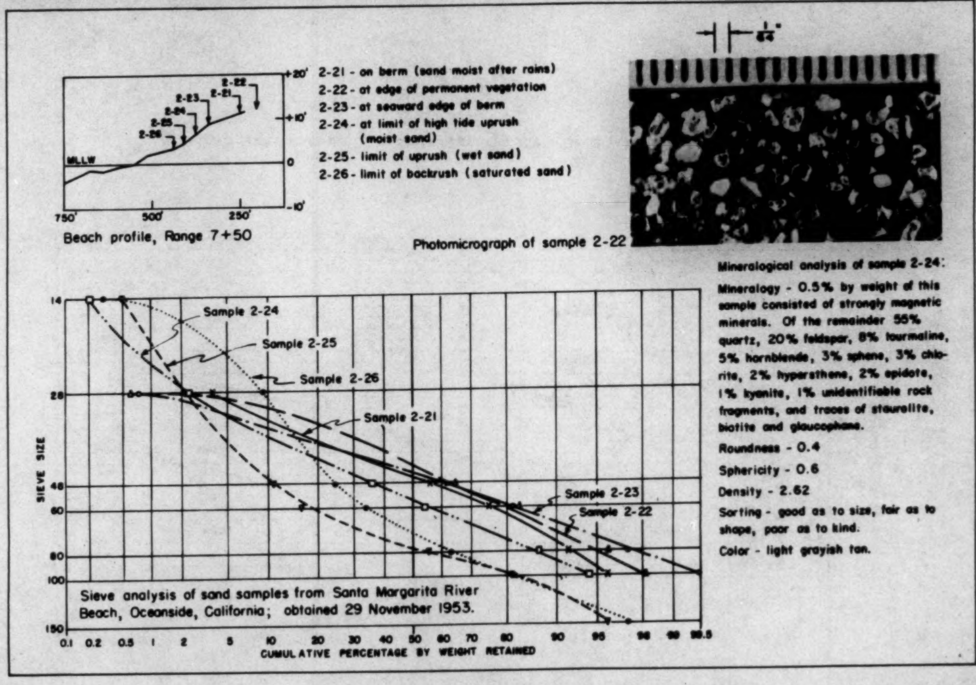


Fig. 5--Aerial photograph of operating area, Santa Margarita River Beach, Oceanside, California



Beach profile, Range 7+50

Photomicrograph of sample 2-22

Mineralogical analysis of sample 2-24:

Mineralogy - 0.5% by weight of this sample consisted of strongly magnetic minerals. Of the remainder 55% quartz, 20% feldspar, 8% tourmaline, 5% hornblende, 3% sphene, 3% chlorite, 2% hypersthene, 2% epidote, 1% kyanite, 1% unidentifiable rock fragments, and traces of staurolite, biotite and glaucophane.

Roundness - 0.4

Sphericity - 0.6

Density - 2.62

Sorting - good as to size, fair as to shape, poor as to kind.

Color - light grayish tan.

Sieve analysis of sand samples from Santa Margarita River Beach, Oceanside, California; obtained 29 November 1953.

Fig. 6--Analysis of beach sand

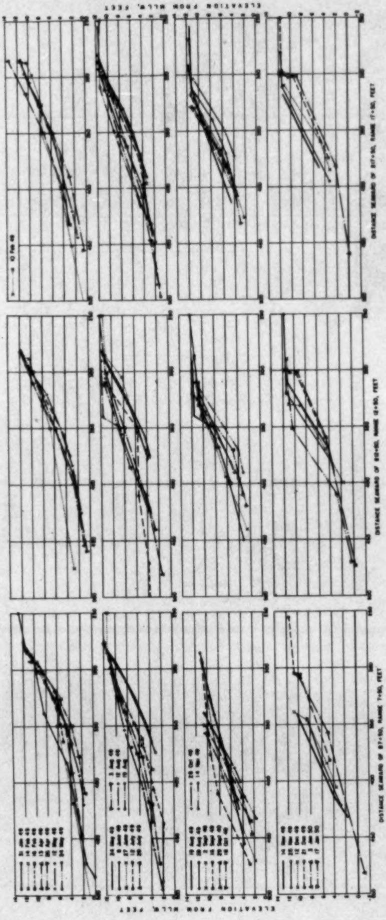


Fig. 7--Beach face profiles, Santa Margarita River Beach, Oceanside, California, 1949

There are basically three types of beach changes. The first is the long-range change which depends upon changing sand supply and changing meteorological conditions. The second is the seasonal change due to long intervals of high surf during 'winter' meteorological conditions, long intervals of low surf during 'summer' meteorological conditions, and increased sand supply from flooding rivers. The third is the short time change due to rapidly changing surf conditions, such as when a near-coastal wind generates short high waves during a period of normally long low waves.

The data have been presented in two figures. In Figure 4 are presented the profiles, measured to a depth of about 25 ft below MLLW. In Figure 7 are shown (using a larger scale) the profiles of the beach face.

It can be seen that, in general, the width of the berm increased during the summer and decreased during the winter. However, the three sets of profiles were not consistent. For example, considerable sand was deposited on the beach face on Range 7+50 between September 2 and 16, 1949, while erosion took place between September 16 and 29, 1949; on Range 12+50 a slight amount of erosion occurred between September 2 and 16, 1949, as well as between September 16 and 29, 1949; and on Range 17+50 there was some slight deposition between September 2 and 16, 1949, and some slight deposition between September 16 and 29, 1949. Some of these apparent discrepancies can be explained by the presence of cusps on the beach during some periods of time; thus, one profile may be across the ridge of a cusp, while another across the hollow of a cusp. This condition makes it very difficult to obtain an accurate picture of what is happening unless a large number of ranges are surveyed. Certain changes were of such a magnitude, however, that they were observed along all three ranges; for example, between December 12 and 21, 1949, a near-coastal storm occurred and severe erosion took place along the entire beach, and a pronounced scarp was formed.

One apparent point of interest, although there is an unfortunate lack of data, is the increase of sand on the beach face during January. It will be noted that in January, 1949, on Range 7+50 and in January, 1950, on Range 12+50 (the only ranges which were sounded) there was a seaward building of the beach face. It will be further noted that during January, 1950, the waves were very low. Unfortunately there were no wave measurements made during January, 1949.

The three series of offshore profiles were more consistent than were the series of onshore profiles. It can be seen that, although a distinct bar was often lacking, there usually was a step present, but almost never was there a time when neither bar nor step were present. It can further be seen that, although the profiles were constantly changing, they were always within rather remarkably narrow limits. The total vertical variation at any distance offshore was always less than ±4 ft from the mean. It appears as if the beach never reaches an equilibrium condition in the true sense of the word, but rather is in dynamic equilibrium.

Because of the relationship between wave steepness and beach profile found in laboratory work [BEACH EROSION BOARD, 1936; JOHNSON, 1953; SAVILLE, 1950], a similar relationship was sought from these data. Although no definite relationship was found, it is believed that the two-week intervals between profiles was so large that adequate data were not available.

The laboratory studies have shown that for waves steeper than 0.03 the 'storm' profile existed (that is, a bar formed), and for values less than 0.025 no bar was present; while for values of wave steepness in between, the regions were unstable. It is readily apparent that this is not the case in the data measured at Santa Margarita River Beach. In fact, the wave steepness never came near the critical value of 0.03, and a bar or a step usually was present. The greatest wave steepness measured was about 0.008, and it was seldom above 0.003. If the criteria are correct, then the reason they do not seem to apply to natural beaches may be (1) the beach is never in equilibrium, or (2) the waves in nature are quite variable and the highest during a storm may well be steeper than the values shown, which are those of the 'significant' wave.

Acknowledgment--This work represents some of the results of research carried out for the Office of Naval Research. The opinions or assertions contained herein are the private opinions of the authors and are not to be construed as official or as reflecting the views of the Navy Department or the Naval Service at large.

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RIPPLE TANK STUDIES OF WAVE REFRACTION

Ning Chien

Abstract--When the shore line and offshore contours are straight and parallel, wave refraction is governed by Snell's law, which states that the sine of the angle between the wave crest and the bottom contour is proportional to the velocity of wave propagation. Snell's law was verified in this study by analyzing the photographic records of wave refraction at a model beach with 1/40 slope and a straight shore line in a ripple tank. This study covers uniform waves with three different periods, non-uniform waves, and three initial angles of wave approach. For the longest period waves, the experimental results seemed to give a refraction angle smaller than that indicated by Snell's law.

Introduction--When a wave moves into shoaling water, its velocity of propagation decreases as the depth decreases and continues to do so until the wave breaks. If waves approach the shore at an angle, the inshore portion of the wave front travels slowly while the portion in deeper water races ahead. Waves thus change direction and swing around in such a manner that the crests tend to conform to the bottom contour. This phenomenon is known as wave refraction.

Wave refraction plays an important role in coastal and harbor works, since it governs, together with the direct shoaling effect, the wave heights along the coast. The breaking of waves obliquely to the coastline also induces a longshore current which, combined with the agitating action of breaking waves, is the primary factor in causing littoral sediment transport [JOHNSON, 1952]. The fact that the bending of the waves conforms to the bottom configuration can also be used to estimate profiles of inaccessible beaches, and this has an important bearing on the planning of landing operations on enemy-held beaches in time of war [WILLIAMS, 1947].

In the case of a straight shore line and parallel offshore contours, wave refraction can be determined by applying what is known as Snell's law [O'BRIEN, 1942]

$$\sin \alpha / \sin \alpha_1 = C/C_1 \qquad (1)$$

where α and α_1 are angles between the wave crest and the bottom contour at any two points along the orthogonal to the wave crest, and C and C_1 are the corresponding velocities of wave propagation at the points where α and α_1 are measured.

In using (1) to determine the position of wave crests at the surface, it is necessary to know the direction and velocity of the waves at a certain reference point 1. This reference point is generally taken in deep water where the direction and velocity are constant. In this study, the reference point was taken at the toe of the beach beyond which the depth of flow remained constant.

The wave velocity is given by

$$C = \sqrt{(gL/2\pi) \tanh (2\pi d/L)} \qquad (2)$$

where L = wave length, g = gravitational constant, and d = depth beneath the still water surface. Eq. (2) is true for waves with low steepness (wave height $< 1/200$ wave length).

The wave velocity can also be expressed by the wave length divided by the wave period T

$$C = L/T \qquad (3)$$

Snell's law has been used quite extensively in the past as the basis of wave refraction studies, and it is the purpose of this investigation to present experimental evidence of its general applicability and possible limitations.

Experimental apparatus--The experiment was conducted in a 4-ft wide, 20-ft long, and 5-inch deep ripple tank [CHINN, 1949]. A 45×72×3/8 inch glass plate was installed at the middle of the

tank bottom. At one end of the tank a water-supply line and drain were provided for control of the water depth. A plunger-type wave generator, supported by a movable frame, was located on the opposite end of the tank. The wave period was controlled by changing the speed of the motor, and wave-height adjustment was provided by an eccentric. The light source was located in an enclosed compartment underneath the tank. The light rays reflected from a 45° mirror passed through in turn a wire grid, the glass section of the tank bottom, the transparent beach and the water in the tank, and projected the images on a 42×42 inch screen supported directly over the glass section and three feet above the water surface. In order to facilitate raising and lowering the screen, a system of strings and pulleys was provided. Light, while passing through a disturbed water surface, will not be uniform in intensity owing to the varying angle of refraction at the surface. According to the principle of light refraction, the images of the wave forms were reproduced on the screen and thereby recorded by a 35-mm movie camera with 25-mm lens at a speed of 28 frames per second and at a focal distance of five feet.

The beach was made of 0.25-inch transparent lucite plate. It had a slope of 1/40 and a straight shore line 1.5 ft wide, and extended 2.83 ft to the sea. The beach was oriented at an angle α_1 with the wave generator with two sides parallel to the side walls of the ripple tank. A thin guide wall was installed along each side of the beach to eliminate shock waves generated by an abrupt change of water depth. The sharp-edged toe of the beach plate was taped down on the bottom of the ripple tank. Black tapes were fastened on the back side of the beach plate to indicate the base line, range line, and control points used in the measurements.

Experimental procedure and method of analysis--The beach was first installed in the ripple tank and water introduced into the tank to cover the entire beach plate. The water surface and the beach profile along the range line were measured to 0.001 ft by a movable point gage. Part of the water was then drained to maintain a still water depth of 0.069 ft in the tank. The beach under still water and an electric clock in motion were then filmed separately, allowing one to determine the length and time scale of the photographic records respectively. The wave generator was put in action starting at the lowest speed (or the longest wave period). The wave period was determined by measuring the time, in seconds, for 100 waves to pass a fixed point and dividing by 100. After the wave pattern became steady, its images on the screen were recorded by the camera for a length of time of about six seconds. The motor speed of the wave generator was then changed to a shorter wave period, and movies of the wave forms over the beach were taken again. A total of three different wave periods, varying from 0.39 to 0.83 sec, was studied. The beach was constructed on a length scale ratio of 1/500, and this gave corresponding wave periods of 8.70 to 18.50 sec in the prototype. After each run, water was drained from the tank, and the beach plate was re-oriented to another angle with respect to the wave machine. The whole process as described above was then repeated.

Table 1--Characteristics of the waves and the beach

(Scale ratio of the model beach: length scale, 1/500; time scale, 1/22.4)

Run number	Beach			Waves				
	Still water depth	Orientation	Profile	Description	Wave period		Wave length in deep water	
					Model	Prototpye	Model	Prototype
	ft				sec	sec	sec	sec
1-A	0.068	50	Slightly concave upward	Uniform waves	0.83	18.5	3.50	1750
1-B					0.60	13.4	1.84	920
1-C					0.40	9.8	0.80	400
2-A	0.069	34	Essentially at 1/40 slope	Uniform waves	0.81	18.1	3.36	1680
2-B					0.60	13.5	1.86	930
2-C					0.39	8.7	0.77	385
2-D				Non-uniform waves	0.30	6.6	0.45	223
					0.53	11.7	1.42	710
3-A	0.069	15	Essentially at 1/40 slope	Uniform waves	0.77	17.2	3.03	1515
3-B					0.59	13.1	1.76	880
3-C					0.39	8.8	0.79	395

In Run 2 non-uniform waves were generated by continuously and quickly increasing and reducing the speed of the wave generator motor, and the wave patterns were recorded. Table 1 gives the characteristics of the waves and the beach for each run.

Analysis of the photographic records involved the following steps:

(a) The film of the beach under still water was projected on a working table and the base line, range line, and control points were drawn on a large sheet of paper. This determined the length scale of the projected film.

(b) The time scale of the records was determined by examining the movies of the clock in motion.

(c) The films of wave patterns over the beach were then projected on the table; and the sheet of paper was oriented until the base line, range line, and control points drawn on the paper in Step (a) coincided with the corresponding ones on the images.

(d) From the first few projections, a line orthogonal to the wave crests was drawn near the range line. All further measurements were made along this reference orthogonal line. The locations of the base line, the range line, and the reference orthogonal line are shown in Figure 1, which is one of the photographs indicating the pattern of 0.395-sec waves over a 1/40 beach oriented at an angle of 50° with the wave generator.

(e) Starting with one of the projections as time zero, each wave was identified with an appropriate number. In all subsequent projections these waves were identified by the same number.

(f) The distance from base line to each wave crest across the reference orthogonal line was measured. The angle between the wave crest and the base line was also taken.

(g) In this manner every third frame was analyzed. From the wave period and the depth, the wave velocity could be calculated according to (2) and (3). The direction sine of the wave crest was then calculated according to (1) by taking the toe of the beach as the reference point where α_1 was the orientation of the beach with respect to the wave generator and d_1 equaled the still water depth.

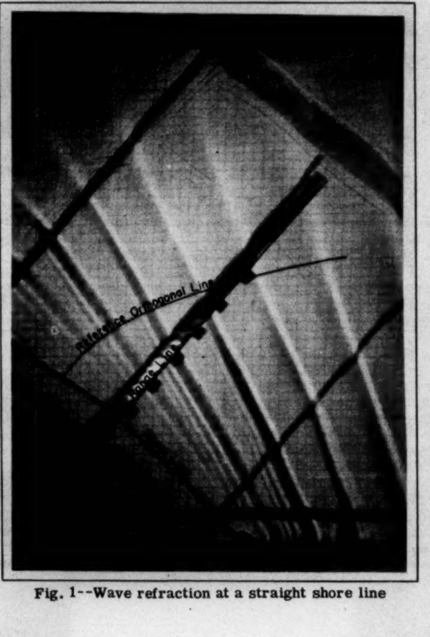

Fig. 1--Wave refraction at a straight shore line

(h) For non-uniform waves, the distance traveled by the wave crests along the reference orthogonal line was plotted against the time elapsed in Figure 2. The time intervals at either side of the wave, T_1 and T_2, were measured; and the period T of the given wave was determined by linear interpolation as follows

$$T = T_1 T_2/[(T_1 + T_2)/2] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

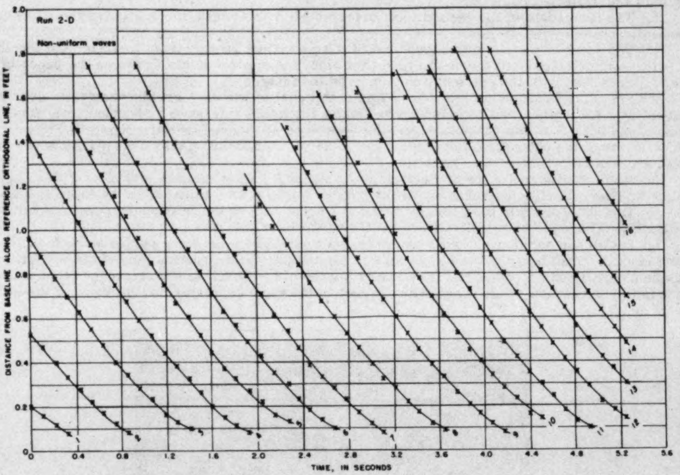

Fig. 2--Approaching of non-uniform waves to a beach in terms of time-distance curve

Experimental results and discussion--The refraction angles, both measured and calculated according to Snell's law, were plotted in Figures 3 to 5 against d/L_0 for three different wave periods and for three different initial angles of wave approach. Among the non-uniform wave group (as indicated in Fig. 2), the refraction angles of waves 7 and 12 were plotted in Figure 6.

A survey of Figures 3 to 6 indicated that, within the limits of accuracy of the experiment, Snell's law was verified, except that possibly the refraction angle was slightly less than that indicated by Snell's law for large wave periods.

The scattering of the experimental data could have been caused by the following experimental errors, or errors in measurement:

(1) After considerable handling, the lucite beach plate tended to bend slightly, resulting in bottom contours which were not exactly straight and parallel. This effect can be seen in Figure 1, where the shore line is slightly curved and is not parallel to the base line.

(2) As the wave length shortened when the wave approached shore, the crests became more sharply defined. However, deeper water wave crests were difficult to identify. This was especially true for waves with longer periods. Close to the breaking zone the images of the wave-crest lines assumed such a wide bend that it was difficult to judge their direction of motion.

(3) In most of the films (Fig. 1 was one of the exceptions), the base line was not clear and its allocation depended on the control points. However, the positions of the control points were affected to a certain degree by the relative positions of the waves. Light refraction due to the water surface undulation might have shifted the images of the control points on the screen from their true positions. In other words, the same wave in subsequent projections might not have been oriented with respect to the same base line.

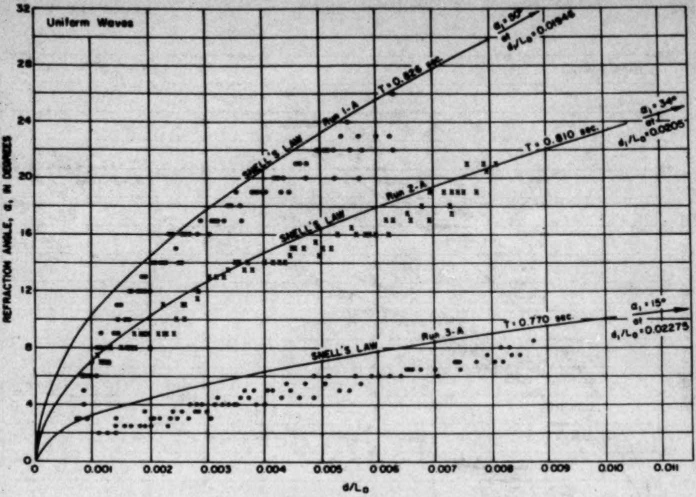

Fig. 3--Refraction of long-period uniform waves

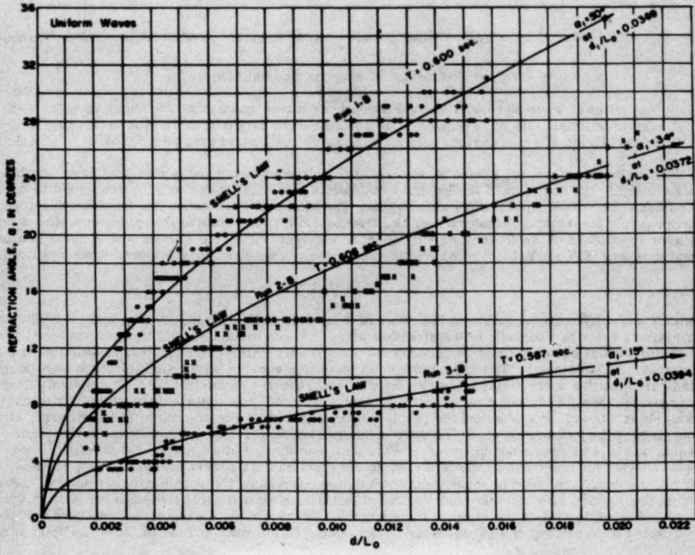

Fig. 4--Refraction of intermediate-period uniform waves

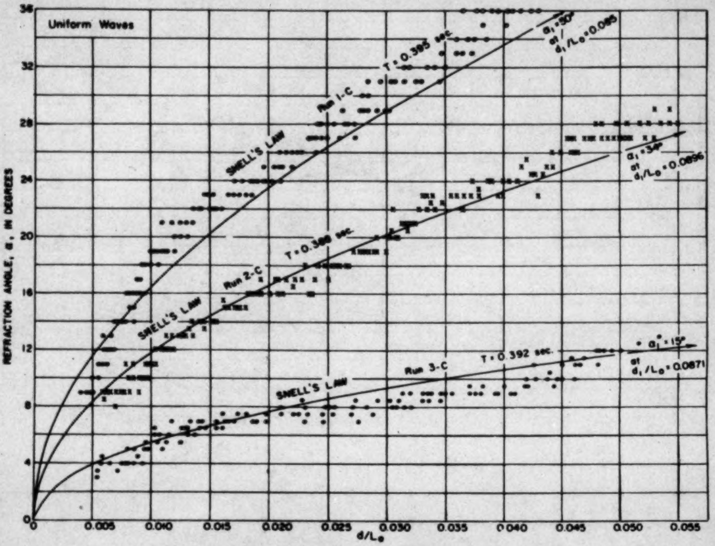

Fig. 5--Refraction of short-period uniform waves

The effect of wave steepness on wave velocity as waves approached the shoaling water was believed to be small. As wave lengths in all the runs were larger than 0.075 ft, according to CHINN [1949], the effect of surface tension on wave velocity could also be ignored.

Despite these errors, Figure 3 indicated that for the longest wave period (and hence the longest wave length), the deviation of the experimental points from Snell's law was too consistent to be accounted for by experimental difficulties alone. The theory of wave refraction has been developed from purely theoretical considerations by LOWELL [1949], who studied the characteristics of waves which approached obliquely into a gently shoaling straight beach. He started with a linear shallow water theory [STOKER, 1947] in which the wave velocity was given by the approximate equation

$$C = \sqrt{gd} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

which was sufficiently accurate in the range of d/L_0 used in this study. By assuming that the wave amplitude remained periodic in the direction parallel to the beach and with time, the original partial differential equation could be reduced into an ordinary differential equation containing the wave number as a parameter. The asymptotic solution of this equation in the limit of large wave number indicated that the wave crests were refracted in accordance with Snell's law. The analysis thus showed that Snell's law could be expected to hold good in shallow water only when the wave length was short. Lowell also attacked the problem by considering the bottom slope to be uniform, without making the assumption about the wave number being large. The solution of the differential equation could be expressed in terms of Whittaker functions. Unfortunately, the solution is not well adapted for computation, since the Whittaker functions are poorly tabulated at the present time. No deduction could be made from the solution concerning the possible direction of deviation from Snell's law, although this study indicated that the refraction angle tended to be smaller than that indicated by Snell's law at large wave lengths. Perhaps it is interesting to note here that the refracted wave pattern of a 16-sec wave at Oceanside, California, on June 16, 1944, as determined

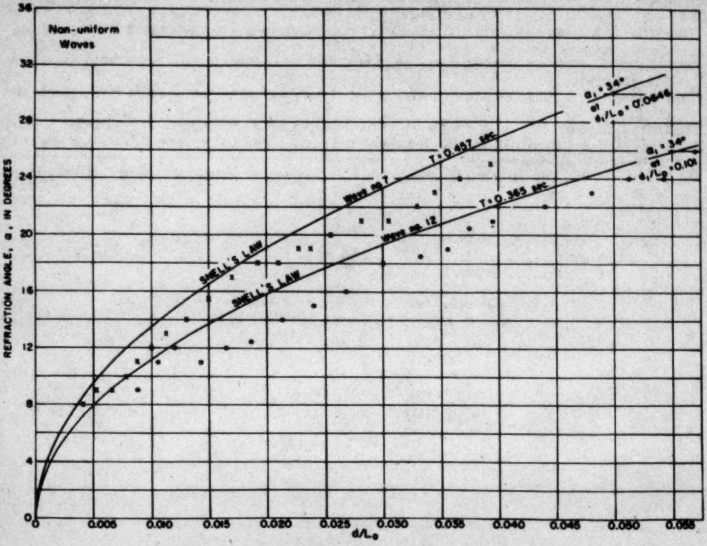

Fig. 6--Refraction of non-uniform waves

from aerial photographs, also seems to give refraction angles slightly smaller than those given by Snell's law [SVERDRUP and MUNK, 1944].

Ocean waves are seldom regular. Even in the laboratory, a wind of constant velocity blowing over the water surface generates waves with a spectrum of heights and periods [JOHNSON and RICE, 1952]. In addition, when wave trains of different velocities meet, they also superimpose and result in a complicated wave pattern. For instance, the resultant waves will be short-crested if the component trains are traveling in different directions. In consequence, the inshore waves are often non-uniform in that the wave length, period, and velocity differ from one wave to another. However, in shallow water the wave velocity can very well be represented by (5), which indicates that the wave velocity is independent of wave length. From this we may conclude that non-uniform waves refract essentially the same as the uniform waves in shallow water, and the experimental evidence seems to bear this out.

In conclusion, this study essentially verified Snell's law on refraction of ocean waves. The experimental results, however, call for additional theoretical research in dealing with refraction of waves of long wave length.

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UNSTEADY FLOW IN POROUS MEDIA BY MEANS OF A HELE-SHAW VISCOUS FLUID MODEL

David K. Todd

Abstract--The problem of unsteady flow in porous media was investigated for the two-dimensional case by a model analogy consisting essentially of an oil flowing through a narrow glass channel. The apparatus, known as a Hele-Shaw viscous fluid model, avoided the difficulties of measuring flow in porous media. The model was calibrated by steady flow measurements. Unsteady flows, composed of sudden releases of oil into and out of the channel, were recorded and analyzed. Results were presented in graphical form using dimensionless parameters. Agreement with numerical solutions of the basic nonlinear differential equation, as applied to gas flow through porous media, was obtained. A study of a series of solitary sine waves was made as a model analogy of the damping of a flood hydrograph in a ground-water table adjacent to a stream. Results indicated that the damping rate was independent of both amplitude and period of the flood wave and that the damping distance was a function of the period but not of the amplitude.

Introduction--The movement of fluids through porous media is one of great complexity, both from mathematical and from laboratory or field standpoints. Nonlinear differential equations of unsteady flow, inadequate definition of the free surface, a variable zone of partial saturation, variable permeability, and apparent rather than actual velocities include some of the basic problems confronting investigators in this field. Frequently model studies, and particularly analogies, can circumvent some of these problems. This study describes the usefulness of one such model analogy. Because ground-water flow problems prompted this investigation, results are interpreted with the thought of ground-water flow in mind.

The Hele-Shaw viscous fluid model consists essentially of two closely-spaced parallel glass plates forming a narrow channel through which a viscous liquid flows. A regulating reservoir is located at one end of the channel. Data are obtained from photographic records of the free surface of the liquid. As a model of ground-water flow, the channel represents a two-dimensional cross-section of an unconfined homogeneous isotropic aquifer, while the regulating reservoir may be considered as any body of open water which the aquifer intersects. One of the major advantages of the Hele-Shaw model is its clearly-defined free surface which eliminates the broad capillary zone of partial saturation that complicates studies of sand models.

Professor H. S. Hele-Shaw at University College, Liverpool, England, developed the first model of this type in 1897 for demonstrations of streamline flow patterns around variously shaped boundaries [HELE-SHAW, 1897]. Subsequent work resulted in improved model designs [HELE-SHAW, 1898, 1899]. DACHLER [1936] was the first to suggest applying the model to ground-water flow studies, followed by PARR [1937] who described a remarkably similar 'fluid-flow analyzer' to show laminar flow around objects. RIEGELS [1938] constructed a Hele-Shaw apparatus to study steady flow around a cylinder. GUNTHER [1940ab] reported on an extensive investigation of the model analogy as applied to flows in porous media with different boundary conditions. Recently the Hele-Shaw apparatus was used as a ground-water flow model in Holland to study hydrologic balance in the polders [DIETZ, 1941, 1944]. Later modifications of this model made it possible to simulate precipitation, irrigation, and evaporation effects on the ground-water table [KRUL and LIEFRINCK, 1946], while SANTING [1951ab] discussed its adaptability to study of sea-water intrusion problems in coastal aquifers. Recently in the United States the model was employed to facilitate drainage studies [HOWLAND, 1943; CORPS OF ENGINEERS, U. S. ARMY, 1946; KELLOGG, 1948; CASAGRANDE and SHANNON, 1952].

Model theory--The mathematical proof that observed streamlines in a Hele-Shaw model represent a two-dimensional picture of potential flow was developed by STOKES [1899]. The derivation stems directly from the generalized Navier-Stokes equations of motion. Since the derivation appears in several texts, including LAMB [1932], DACHLER [1936], GOLDSTEIN [1938], and STREETER [1948], it need not be repeated here.

For the steady-flow case and by making the requisite Dupuit-Forchheimer assumptions, the mean velocity of flow in the model may be expressed as

$$v_m = -\frac{b^2 \rho g}{3\mu}\frac{dh}{dx} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where b is the half-width of the channel; ρ, g, and μ are the density, gravity, and viscosity terms, respectively; and dh/dx is the surface slope. The analogy to the Darcy Law is apparent. By varying b and μ, the model-prototype velocity ratio can be determined for any desired permeability value. Selection of the length scale ratio allows the time scale to be defined for any simulated aquifer and boundary conditions.

The equation for unidirectional flow in the unsteady state is

$$\frac{\partial h}{\partial t} = -\frac{b^2 \rho g}{3\mu}\left[\left(\frac{\partial h}{\partial x}\right)^2 + h\frac{\partial^2 h}{\partial x^2}\right] \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where t is time. This nonlinear equation has no known exact solutions for generalized boundary conditions. The unsteady heat transfer equation [CARSLAW and JAEGER, 1947] can be derived from (2) by neglecting the squared slope term, by replacing h by its mean, and by replacing the constant group with a diffusivity constant.

Experimental equipment and procedure--The model was composed of two pieces of 1/2-inch plate glass resting on edge in a base support of cold-rolled steel with a sheet neoprene separator. A plate spacing of 0.2096 cm was obtained by inserting strips of aluminum wrapped in Oiltite fiber sheet packing at the top and bottom of the channel. Thumb screws, inserted in tapped horizontal holes in the side of the base support, maintained proper compression along the bottom, while C-clamps served this purpose along the top. Small wood and aluminum bearing plates avoided all glass-metal contacts. To support the glass in a vertical position, four side supports were built from strap iron and pipe. A regulating reservoir of sheet iron was located at one end of the channel. Neoprene tubing sealed along the channel bottom between the glass plates and at the reservoir-channel junction. A small overflow lip clamped to the glass controlled the channel outflow. This lip directed the oil into an overflow pan, after which it passed through a pipe to the sump. A 1/4-horsepower, alternating-current motor drove a small gear pump which lifted the oil from the sump to a storage tank connected with the regulating reservoir. Flow into the regulating reservoir was governed by a valve, while an adjustable depth overflow pipe and valve regulated the outflow. A vertical brass slide gate seated in a slot between the regulating reservoir and channel and fitted with a handle allowed sudden releases of oil into and out of the channel to be made. The oil level in the regulating reservoir was observed by means of a Stevens water-level recorder. For the fluid in the model, about 20 gallons of clear mineral oil, marketed as 'Freezene-Medium Heavy, were employed.

Figure 1 shows a schematic diagram of the model and includes channel dimensions. The capillary rise of the oil between the glass plates was determined from the surface tension and contact angle of the oil. The equilibrium condition for a rectangular channel between the lifting force due to surface tension and the resisting force due to hydrostatic pressure is

$$2L\sigma\cos\theta = 2bL\rho gh \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where L is the channel length, σ is the surface tension, θ is the contact angle, and h is the capillary rise. Solving for h gives

$$h = \frac{\sigma\cos\theta}{b\rho g} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

The oil spread easily on a polished glass surface, indicating an assumption of zero contact angle as a first approximation. The surface tension was measured to be 41.5 dynes/cm. Inserting these values, together with $b = 0.1048$ cm, $\rho = 0.877$ gm/cm^3, and $g = 980$ cm/sec^2, in (4) yields 0.46 cm for the capillary rise. This value applies only to the static case, since the contact angle depends upon whether the interface is advancing or receding and upon whether the glass is free of oil or has a molecularly adsorbed oil layer. In any case, the above value represents a maximum.

Steady flows were measured first in the channel. The overflow pipe and outflow lip governed the inflow and outflow heights, respectively. The free surface of the oil was followed with grease

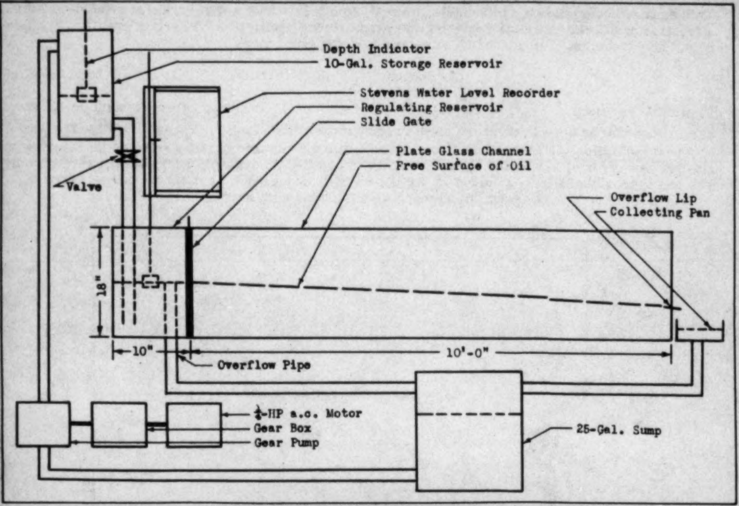
Depth Indicator
10-Gal. Storage Reservoir
Stevens Water Level Recorder
Regulating Reservoir
Slide Gate
Plate Glass Channel
Free Surface of Oil
Valve
Overflow Lip
Collecting Pan
18"
10"
10'-0"
Overflow Pipe
¼-HP a.c. Motor
Gear Box
Gear Pump
25-Gal. Sump

Fig. 1--Schematic diagram of model setup

pencil marks to ascertain when a steady state had been attained. Flow rates were determined by weighing volumes of oil collected in a beaker held under the outflow lip for known time intervals. Oil temperatures were measured in the regulating reservoir so that viscosities and densities could be corrected to a standard temperature.

Motion pictures recorded the free surface of the oil during unsteady flows. The surface appeared as a well-defined black line when viewed from the side, so that oil depths at various distances and times could be scaled directly from projections of individual frames of the motion-picture film. A small amount of red dye added to the oil facilitated proper location of the free surface line. Grid paper mounted behind the channel provided a basis for scaling depths. Two synchronized 35-mm cameras were required to cover the length of the channel, while a stencil and electric clock were mounted above the channel to identify runs and times, respectively.

Unsteady flows studied included sudden releases of oil into and out of the channel and solitary sinusoidal waves. The first flow type occurred after filling the reservoir with oil and pulling the slide gate. The rise of oil in the channel was termed 'buildup,' whereas the reverse flow situation was termed 'drawdown.' The outflow end of the channel was sealed during these runs. Sinusoidal flows were obtained by plotting sine curves of various amplitudes and periods on the recorder chart and following these curves with the pen arm attached to the float rod. Reservoir oil levels responded to proper manipulation of inflow and outflow valves.

Experimental results and analysis--Thirteen steady flow runs were measured to determine the flow characteristics of the model channel. Referring to (1), the steady flow rate may be given as

$$Q = Av_m = -(2bh)\left(\frac{b^2 \rho g}{3\mu}\right)\left(\frac{dh}{dx}\right) \qquad \text{.................... (5)}$$

which, upon separating variables and integrating, becomes

$$Q = \frac{b^3 \rho g}{3\mu L}\left(h_1^2 - h_2^2\right) \qquad \text{.......................... (6)}$$

This equation corresponds to the unidirectional Dupuit-Forchheimer equation of ground-water flow, a function of the plate spacing replacing the permeability coefficient. Inserting previous values of b, ρ, and g, together with $\mu = 1.016$ poise and L = 304.8 cm, gives

$$Q = 1.0648 \times 10^{-3} (h_1^2 - h_2^2) \quad \ldots\ldots\ldots\ldots (7)$$

Plotting Q versus $(h_1^2 - h_2^2)$ on log-log paper (because of the range of values) a straight line results which can be used to compare experimental measurements of Q, h_1, and h_2 (Fig. 2). The observations follow the theoretical line closely, while deviations may be attributed to experimental errors. An error of 1°F in the oil temperature introduces an error of 3.5 to 4.0 pct through density and viscosity changes, an error of 0.001 inch in b causes a 3.6 pct error, and an error of 0.01 inch in h_1 or h_2 can amount to as much as a four per cent error.

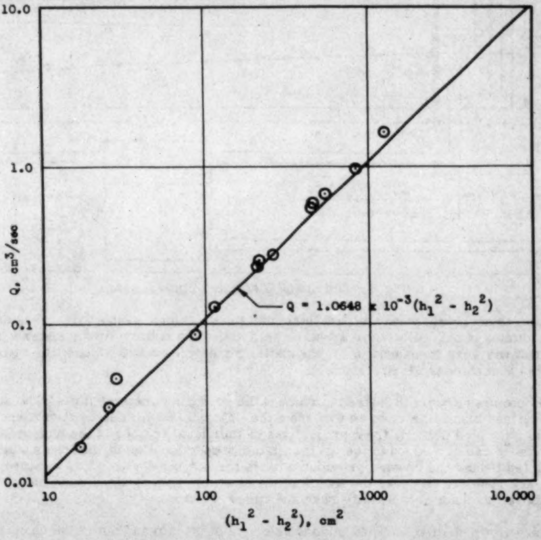

Fig. 2--Relation of Q to $(h_1^2 - h_2^2)$ for steady flows

The Dupuit-Forchheimer equation accurately predicts the flow rate between specified boundaries, but it does not predict the free surface profile because of the limiting assumptions necessary in the derivation [MUSKAT, 1937; JACOB, 1950]. For unidirectional flow the error increases with the slope and consequently in the direction of flow, except in the vicinity of the outflow due to a drawdown effect. The observed profile should lie above the computed one, the difference at the outflow being known as the surface of seepage. Data from one steady-flow run in the model channel, listed in Table 1, illustrate the relationship of the observed and computed profiles. Observed oil depths are corrected for capillarity.

In analyzing the drawdown and buildup data of unsteady sudden release runs, the problem of no exact analytical solutions for (2) arises. Several approaches appear in the literature. FELBER [1930, 1931], WERNER and NOREN [1951], and BAUMANN [1952], in applying the equation to groundwater problems, assumed the square of the free surface slope negligible in comparison to the other term and the surface deviations small in relation to the depth, so that a mean value for h could apply. Depth variations in the model channel violate these assumptions, so that the equation in

Table 1--Comparison of observed and computed depths along a steady-flow profile

x/L	h_o	h_c	$h_o - h_c$
	cm	cm	cm
0.0	22.6	22.6	0.0
0.1	21.6	21.5	0.1
0.2	20.6	20.4	0.2
0.3	19.4	19.2	0.2
0.4	18.4	18.0	0.4
0.5	17.2	16.6	0.6
0.6	15.9	15.1	0.8
0.7	14.5	13.5	1.0
0.8	12.8	11.6	1.2
0.9	11.0	9.4	1.6
1.0	7.4	6.4	1.0

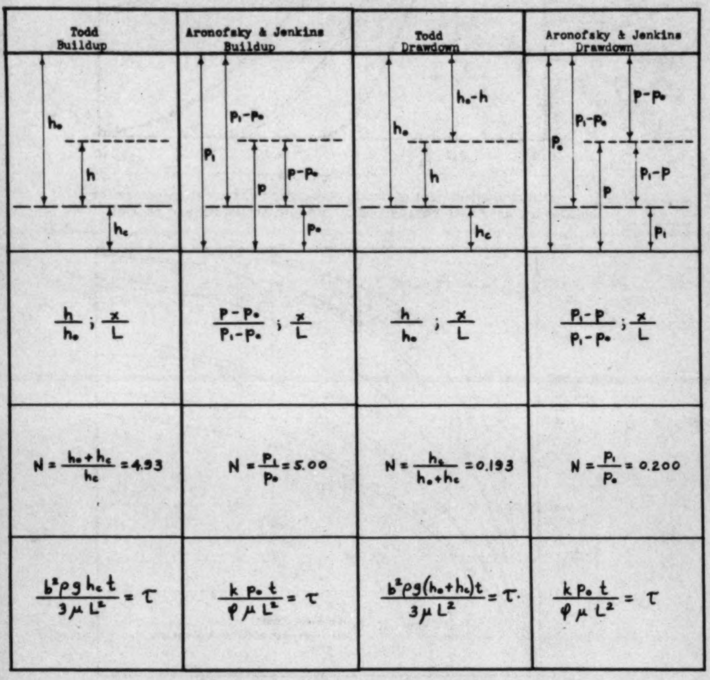
Todd Buildup
Aronofsky & Jenkins Buildup
Todd Drawdown
Aronofsky & Jenkins Drawdown
h_o
h
h_c
p_1
$p_1 - p_o$
p
$p - p_o$
p_o
$h_o - h$
h_o
h
h_c
p_o
$p_1 - p_o$
$p - p_o$
p
$p_1 - p$
p_1
$\frac{h}{h_o}$; $\frac{x}{L}$
$\frac{p - p_o}{p_1 - p_o}$; $\frac{x}{L}$
$\frac{h}{h_o}$; $\frac{x}{L}$
$\frac{p_1 - p}{p_1 - p_o}$; $\frac{x}{L}$
$N = \frac{h_o + h_c}{h_c} = 4.93$
$N = \frac{p_1}{p_o} = 5.00$
$N = \frac{h_c}{h_o + h_c} = 0.193$
$N = \frac{p_1}{p_o} = 0.200$
$\frac{b^2 \rho g h_c t}{3 \mu L^2} = \tau$
$\frac{k p_o t}{\varphi \mu L^2} = \tau$
$\frac{b^2 \rho g (h_o + h_c) t}{3 \mu L^2} = \tau$
$\frac{k p_o t}{\varphi \mu L^2} = \tau$

Fig. 3--Comparison of buildup and drawdown parameters for this study and for that by Aronofsky and Jenkins

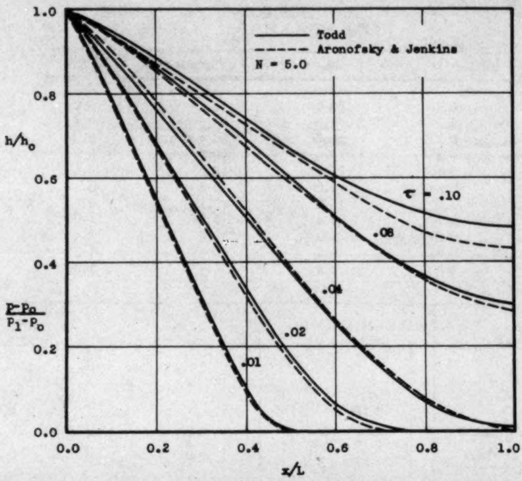

Fig. 4--Dimensionless plot of depth, distance, and time parameters for buildup together with corresponding data by Aronofsky and Jenkins

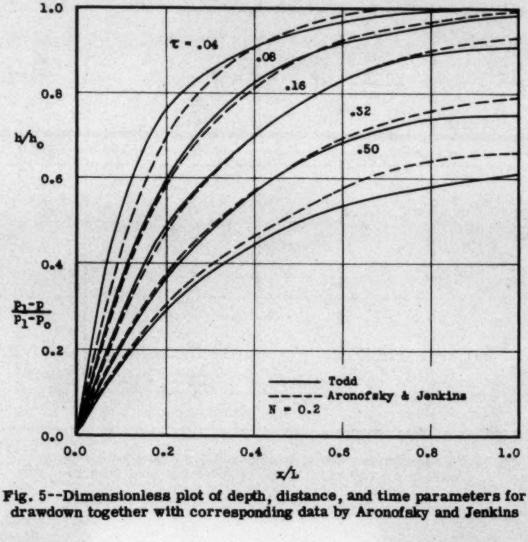

Fig. 5--Dimensionless plot of depth, distance, and time parameters for drawdown together with corresponding data by Aronofsky and Jenkins this form cannot be used. MUSKAT [1937] applied the method of 'succession of steady states' to radial flow problems, while ROBERTS [1952] showed that by dividing the time into a sequence of small consecutive intervals the flow equation could be linearized. Recently an electric analogy approach [McCANN and WILTS, 1949] was applied to the similar problem of isothermal flow of gases through porous media [GREEN and WILTS, 1952]. Some of the most accurate solutions to the equation are contained in a report by ARONOFSKY and JENKINS [1952] on unsteady flow of gases through porous media. By expressing the equation as a finite-difference equation, punch-card machines produced answers for specified boundary conditions.

Graphical solutions, developed by PUTNAM [1943], involving dimensionless parameters, are utilized here. By defining h_c as the constant oil depth at the overflow pipe, h_o as the maximum depth above h_c, and h as any depth above h_c, boundary conditions for the two flow cases may be expressed as follows:

Buildup	Drawdown
$H(x, 0) = h_c$ for $0 < x < L$	$H(x, 0) = (h_o + h_c)$ for $0 < x < L$
$H(0, t) = (h_o + h_c)$	$H(0, t) = h_c$
$H(L, \infty) = (h_o + h_c)$	$H(L, \infty) = h_c$
$\partial h/\partial x\,(L, t) = 0$	$\partial h/\partial x\,(L, t) = 0$

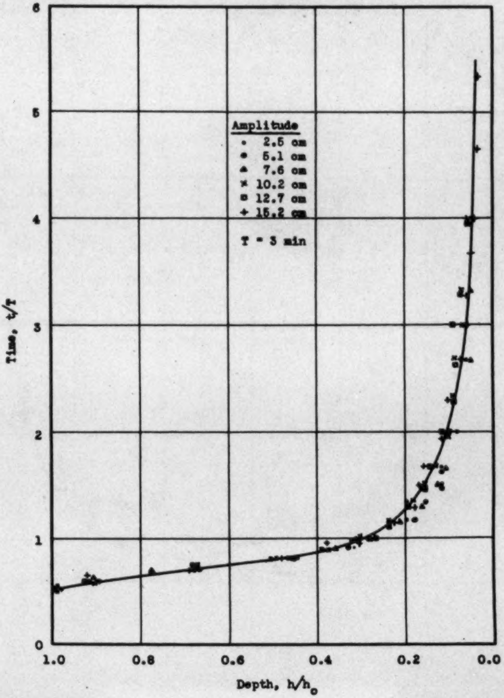

Fig. 6--Relation of t/T to h/h_o for maxima of solitary sine waves with constant period

The notation includes H, a height function; x, distance along the channel; L, channel length; and t, time after release. From these conditions the physical quantities can be related in a functional equation

$$f\,(h, h_o, h_c, c, t, x, L) = 0 \qquad (8)$$

where $c = -b^2\rho g/3\mu$. Combining these quantities into dimensionless parameters, so that, for example,

$$f\,(h/h_o, x/L, cth_c/L^2) = 0 \qquad (9)$$

coordinates are established for a dimensionless plot of the data for specified depth ratios. Let the symbol N be the ratio of the final depth in the channel to the initial depth. Then N exceeds one for buildup and is less than one for drawdown. Figure 3 presents sketches and evaluations for the various parameters required in the dimensionless plots. In order to compare the model channel results with those of ARONOFSKY and JENKINS [1952], comparable terms and parameters also appear in Figure 3. These values apply in the latter study to pressure distributions for various pressure ratios in one-dimensional finite tubes with closed ends. Original notation is retained for reference purposes. Because different values of N and the time parameter (τ) were used in each study, data are reduced to standard values. Interpolated data for the current study were obtained using graphs prepared from the range of Aronofsky and Jenkins' data.

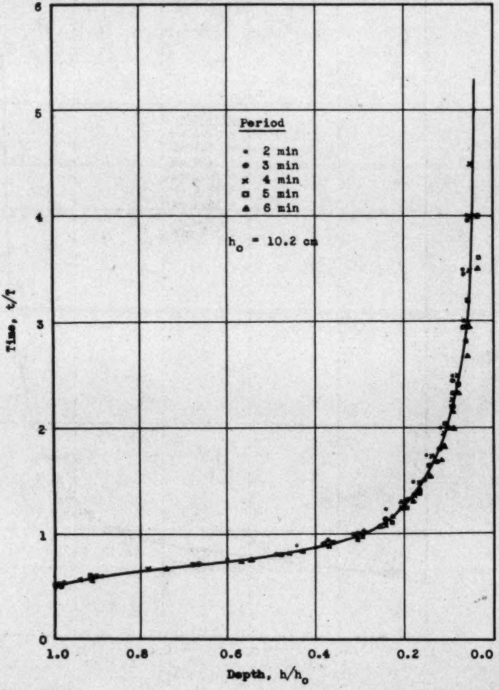

Fig. 7--Relation of t/T to h/h_o for maxima of solitary sine waves with constant amplitude

Figures 4 and 5 show graphically the results of buildup (N = 5.0) and drawdown (N = 0.2) runs, respectively, for the two studies. Nearly identical patterns are indicated. The maximum error amounts to 0.06 (h/h_o). Most of the discrepancies result from decreases in the viscosity of the oil with time and distance. Heat from photoflood bulbs, operating during filming of the runs, account for these changes. The tendency for depths to be too large in buildup and too small in drawdown follows from the above reasoning.

The second type of unsteady flow consisted of solitary sine waves superimposed on an initial constant oil depth. The waves began at the initial depth, rose to a maximum, and returned to the initial depth at the end of the period. Neither a steady-state oscillating system nor an oscillation about a mean value existed for such waves. This type of wave was selected because it approximates the damping of ground-water fluctuations perpendicular to a stream during flood periods. For application of the results to field conditions, a uniform permeability, a vertical bank, no overtopping of the bank by flood crests, and a horizontal ground-water table must be assumed. An experimental investigation by MILLER [1941] differed from this study in that it involved steady-state sinusoidal oscillations in a sand-filled channel.

During the rise of the oscillation, the reservoir depth continuously exceeds the channel oil depth. This difference induces a flow into the channel. At the instant of maximum reservoir depth,

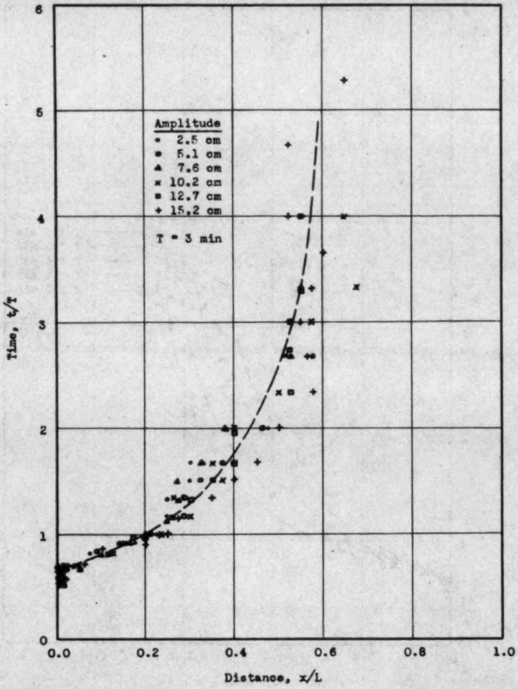

Fig. 8--Relation of t/T to x/L for maxima of solitary sine waves with constant period the reservoir depth remains constant while flow continues into the channel. However, a short time later, the reservoir depth lies below that in the channel entrance, reversing the oil surface slope and initiating a flow from the channel back into the reservoir. This point of flow reversal, which constitutes the maximum channel depth, travels away from the reservoir because of the greater flow rates back into the reservoir. The maximum depth decreases with time as a result of the diverging flow until the oil surface again assumes a horizontal position.

The above physical description of the damping process of a solitary viscous wave can be illustrated by reference to Figures 6, 7, 8, and 9. The dimensionless time ratio, t/T, where t is time and T is the wave period, and the dimensionless height h/h_o, where h is any amplitude and h_o is the initial wave amplitude, are plotted in Figure 6 for constant periods and variable amplitudes. Figure 7 shows the opposite case. The grouping of the data about the mean line indicate that the damping rate is independent of both wave amplitude and period. Figures 8 and 9 show the same cases, but the distance parameter, x/L, which indicates the position of the maximum, replaces the height parameter. Although some scatter occurs in Figure 8, no consistent trend with wave amplitude appears to exist. Much of the scatter may be attributed to difficulties encountered in detecting the maximum positions in the later time portions of the runs. In Figure 9 a pronounced spread of points is seen and a family of lines is sketched through the points corresponding to each period. A functional relationship between damping distance and wave period is implied.

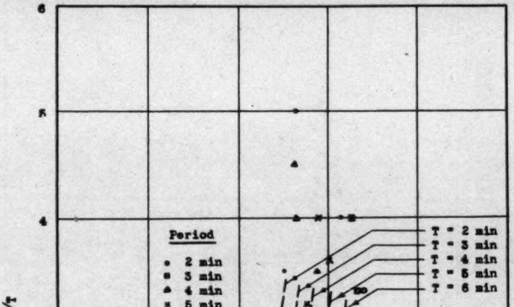

Fig. 9--Relation of t/T to x/L for maxima of solitary sine waves with constant amplitude

The initial depth was constant for all of the sinusoidal runs; consequently, any effect that this factor has on the damping cannot be evaluated. Some errors may exist in these data because the channel was not of infinite length; however, the rapidity of damping would indicate this limitation is not serious.

Conclusions--Steady-flow measurements in the model channel agreed closely with computed flows using an equation equivalent to the Dupuit-Forchheimer equation for steady ground-water flow. The steady-flow profile differed from the computed profile as anticipated.

Except for small differences, analyses of unsteady sudden release data, expressed in terms of dimensionless parameters, concurred with results from gas pressure distributions determined from a finite-difference equation which approximates the basic partial differential equation of unsteady flow. Viscosity changes of the oil were responsible for the small differences observed. Dimensionless plots of maxima of solitary sinusoidal waves in the channel indicated that damping occurred at the same rate regardless of wave amplitude and period, that waves damped out at the same distance for a given amplitude, but that waves damped out at varying distances for varying periods.

The Hele-Shaw apparatus proved to be a versatile tool for unsteady-flow investigations. Its analogy to flow in porous media made it superior to a sand model because of the sharp free-surface boundary, the ease of reading and recording data, and the avoidance of a variable capillary zone. The model can be adapted to other boundary conditions and to permeability variations.

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PLANE POTENTIAL FLOW OF GROUND WATER WITH LINEAR LEAKAGE

Mahdi S. Hantush and C. E. Jacob

Abstract--Potential distributions are found for steady wells idealized as sinks, and tapping uniform confined aquifers into which there is leakage in proportion to the drawdown. Several plane regions are treated, along whose boundaries the potential, flux, or both are specified. The ratio of the conductivity of the aquifer to that of the confining bed is assumed very large so that the refraction of flow lines may be assumed complete as they cross the contact. The leakage, thus considered vertical through the confining bed, is assumedly distributed throughout the thickness of the aquifer as it thus aguments or diminishes the horizontal flow, which is then treated as two dimensional.

Starting with the fundamental solution for an infinite plane region, the solutions for other plane regions are built up by the method of images. The Green's functions for leaky systems are thus obtained for infinite half-planes (two cases), infinite quadrants (three cases), infinite strips (three cases), infinite half-strips (six cases), and rectangles (six cases). Several graphs are given showing potential distributions in special cases and showing the magnitude of drawdown at the well face for various values of the parameters.

The result obtained in Part I of this paper for the infinite plane is extended by the method of images to find solutions for infinite strips, infinite half-strips and for rectangles, in Part II. These solutions are put in forms of series which are convenient for computations. These series are uniformly convergent for all values of x and y except when both are simultaneously taken at the center of the well in which case the series diverges logarithmically to negative infinity. Each of these solutions satisfies the properties of one of the three different types of Green's functions--the first, the second, or the mixed type, but instead of being a harmonic function it satisfies the equation of motion of ground water with linear leakage. Accordingly these solutions may be considered as the Green's functions for systems with linear leakage.

PART I

Introduction--The horizontal flow of ground water in a confined bed may be augmented or diminished by water leaking through semi-pervious confining beds. As a first approximation the rate of vertical leakage, in non-steady as well as steady states of flow, may be considered to vary linearly with the instantaneous difference of head across the confining bed. Strictly speaking, leakage is three dimensional in nature and is rarely vertical. However, provided the permeability contrast of the aquifer and its confining bed is sufficiently great, the leakage may safely be assumed to be vertical and the problem thus considerably simplified.

As flow lines cross the contact between the aquifer and its confining bed they are refracted according to the tangent law of refraction, that is, the tangents of the angles of incidence and refraction are in the same ratio as the respective hydraulic conductivities. If the conductivity of the aquifer is enormously greater than that of its confining bed, as is usually the case, the flow lines may be considered vertical in the confining bed and horizontal in the aquifer. The completely refracted leakage may be thought of as being uniformly distributed throughout the horizontal flow. Hence, the actual three-dimensional flow can be treated as a two-dimensional flow that is augmented or diminished in the direction of the flow by the downward or upward leakage.

Commonly a shallow sand is confined above by a semi-pervious 'clay' or silt that reaches to the surface and in which the ground water is continuously replenished by rainfall, maintaining a more or less uniform head on top of the confining layer (see Fig. 1). Water thus ponded at the ground surface supplies the leakage induced by lowering the head in the confined sand. This problem was analyzed by DE GLEE [1930] and by STEGGEMENTZ and VAN NES [1939] in connection with their studies of the polders in the Netherlands.

In many cases the semi-pervious confining bed is overlain by another aquifer. If the transmissibility of this second aquifer is large, it may effectively maintain constant head above the confining layer despite the downward leakage. This system is analyzed in the same way as the other, however.

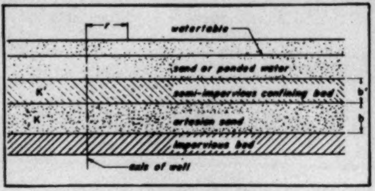

Fig. 1--Diagramatic representation of a leaky aquifer

The problem of steady radial flow to a steady well in a leaky aquifer was solved by JACOB [1946]. He treated two cases, one for a well in an infinite aquifer and the other for a well at the center of a circular aquifer with zero drawdown on its outer boundary. He also obtained the non-steady solution of the second case. He neglected the compressibility of the confining bed and ascribed perfect elasticity to the aquifer.

Equation of plane motion of ground water with linear leakage--The differential equation [HANTUSH, 1949] for non-steady flow in leaky plane aquifers is

$$(\partial^2 s/\partial x^2) + (\partial^2 s/\partial y^2) - (s/B^2) = (S/T)\,(\partial s/\partial t) \quad \ldots\ldots\ldots\ldots\ (1)$$

where s is the drawdown at any point (x, y) in the region of flow and at time t from the start; S is the storage coefficient (volume of water which a unit decline of head releases from storage in a vertical prism of the aquifer of unit cross section [JACOB, 1946]; T is transmissibility of the aquifer (discharge per unit normal width per unit hydraulic gradient); B is a leakage factor equal to $\sqrt{Tb'/K'}$ [HANTUSH, 1949]; and b' and K' are respectively the thickness and the hydraulic conductivity or 'permeability' of the semi-pervious confining bed through which leakage takes place in proportion to the drawdown (see Fig. 1).

In polar coordinates (1) transforms into

$$(\partial^2 s/\partial r^2) + (1/r)\,(\partial s/\partial r) + (1/r^2)\,(\partial^2 s/\partial \theta^2) - (s/B^2) = (S/T)\,(\partial s/\partial t) \quad \ldots\ldots\ (2)$$

When the flow is purely radial, the drawdown does not vary with the polar angle, and (2) reduces to

$$(\partial^2 s/\partial r^2) + (1/r)\,(\partial s/\partial r) - (s/B^2) = (S/T)\,(\partial s/\partial t) \quad \ldots\ldots\ldots\ldots\ (3)$$

The flow is said to be steady if it does not change with time or if $(\partial s/\partial t) = 0$.

Thus depending upon the system of coordinates the steady-state differential equation for plane motion of ground water with linear leakage is given by any one of (1), (2), or (3), with the right-hand side equal to zero.

Green's function for systems with linear leakage--A function $G'(x, y; x_1, y_1)$ depending on the coordinates of two points (x, y) and (x_1, y_1) will be called the Green's function for a system with linear leakage if it has the following properties: (1) Possesses a logarithmic singularity when (x,y) = (x_1, y_1), that is, it becomes infinite as $(-\ln r)$ where $r^2 = (x - x_1)^2 + (y - y_1)^2$. (2) Is regular and satisfies the steady-state equation, namely, $\nabla^2 G' = G'/B^2$ at every other point in the region. (3) Is symmetrical in the two points (x, y) and (x_1, y_1). (4a) Vanishes on the boundary, or (4b) its normal derivative vanishes on the boundary.

If such a function can be found for a given region, then the potential distribution in the interior of the region will be given, if Property 4a is satisfied, by

$$\phi(x,y) = -(1/2\pi)\oint \phi(x_1, y_1)\,[\partial G'/\partial n_1]\,dS \quad \ldots\ldots\ldots\ldots\ (4)$$

and, in case Property 4b is satisfied by

$$\phi(x, y) = (1/2\pi)\oint G'\,[\partial \phi(x_1, y_1)/\partial n_1]\,dS \quad \ldots\ldots\ldots\ldots\ (5)$$

where $\phi(x_1, y_1)$ is a solution of the steady-state differential equation $\nabla^2\phi = \phi/B^2$, n is the exterior normal to the elemental length dS, and the integral is taken over the whole boundary. (The functions in the integrands of (4) and (5) are to have their boundary values before the integrations are performed.)

To develop (4) and (5) one proceeds as follows: Let Figure 2 represent a region enclosed by the curve S, and assume that the Green's function for that region is known. And let (x, y) be the singular point and (x_1, y_1) be the traveling one.

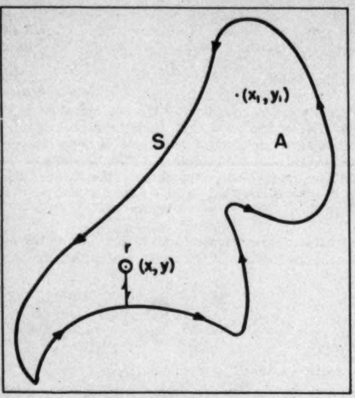

Fig. 2--Closed region for which the Green's function is known

The symmetrical form of Green's formula in the plane is

$$\oint [U(\partial V/\partial n) - V(\partial U/\partial n)]\, dS = \iint_A [U\nabla^2 V - V\nabla^2 U]\, dxdy \quad \ldots . (6)$$

where U and V are functions of x and y.

On letting $U = G'$ and $V = \phi(x_1, y_1)$, the above equation reduces to

$$\oint [G'(\partial\phi/\partial n_1) - \phi(\partial G'/\partial n_1)]\, dS = \iint_A [G'\nabla^2\phi - \phi\nabla^2 G']\, dxdy \quad \ldots . (7)$$

By the second property of G', $\nabla^2 G' = G'/B^2$, and by virtue of the relation $\nabla^2\phi = \phi/B^2$, (7) can be written as

$$\oint [G'(\partial\phi/\partial n_1) - \phi(\partial G'/\partial n_1)]\, dS = \iint_A [G'(\phi/B^2) - \phi(G'/B^2)]\, dxdy = 0\ . (8)$$

Applying (8) to the region of Figure 2, excluding the point (x, y) by a small circle of radius r one obtains

$$\oint [G'(\partial\phi/\partial n_1) - \phi(\partial G'/\partial n_1)]\, dS - \int_0^{2\pi} [G'(\partial\phi/\partial r) - \phi(\partial G'/\partial r)]\, r d\theta = 0 \quad \ldots .. (9)$$

Letting $r \rightarrow 0$ then by the first property of G', $G' \rightarrow -\ln r$ and hence

$$\lim_{r \rightarrow 0} \left[\int_0^{2\pi} G'(\partial\phi/\partial r)\, r d\theta\right] = \lim_{r \rightarrow 0} \left[\int_0^{2\pi} (-r \ln r)(\partial\phi/\partial r)\, d\theta\right] = 0$$

whereas

$$\lim_{r \rightarrow 0} \left[\int_0^{2\pi} \phi(x_1, y_1)(\partial G'/\partial r)\, r d\theta\right] = \lim_{r \rightarrow 0} \left[\int_0^{2\pi} \phi(x, y)(-1/r)\, r d\theta\right] = -2\pi\phi(x, y)$$

By virtue of the above two relations, (9) becomes

$$\oint [G'(\partial\phi/\partial n_1) - \phi(\partial G'/\partial n_1)]\, dS = 2\pi\phi(x, y) \quad \ldots\ldots\ldots\ldots\ldots (10)$$

By Property 4a of G', $G' = 0$ on the boundary S. Hence (10) becomes (4). Similarly, by Property 4b of G', $(\partial G'/\partial n_1) = 0$ on S, in which case the equation becomes (5).

The method of images--If a system of sinks exists in a region, the resultant potential distribution in the region is the sum of the potentials contributed by each sink separately. Furthermore, the normal derivative of the resultant potential at any one point of the boundary of the region is the sum of the normal derivatives of the potentials at that point due to the individual sinks. Thus, if there are m sinks and the potential due to the j^{th} one is ϕ_j, then the potential distribution of the whole system is

$$\phi = \sum_{j=1}^{m} \phi_j \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

and, at any one point on the boundary

$$(\partial\phi/\partial n) = \sum_{j=1}^{m} \partial\phi_j/\partial n \quad \ldots\ldots (12)$$

where n is the outward normal to the boundary at that point.

Now, if this system of sinks is reflected negatively in the boundary of the regions (that is, negative images of sources are placed on the other side of the boundary), then the resultant potential on the boundary is, according to (11), equal to zero because for each sink of negative potential there is a source of positive potential equidistant from the boundary. This process of 'reflection' may have to proceed back and forth infinitely many times, depending on the form of the boundary. The potential may be made arbitrarily to have a constant value on the boundary by imposing a constant potential over the region.

At any point on the boundary, the normal derivative of the potential due to any sink is the negative of that due to its positive image. Therefore, if the images of the system of sinks are also sinks, then by (12)

$$(\partial\phi/\partial n) = \sum_{j=1}^{m} (\partial\phi_j/\partial n) + \sum_{j=1}^{m} [\partial\phi_j/\partial(-n)] = 0$$

That is, the normal derivative of the resultant potential vanishes on the boundary.

Steady-state solutions--Several problems of practical interest require the determination of the drawdown produced by a well discharging at a steady rate from a leaky aquifer on whose boundaries the head, the flux, or both are known. In what follows it is always assumed that the lateral boundaries of the regions are vertical and that they cut completely through the artesian aquifer. The conditions along those boundaries are uniform, in the vertical direction.

Because its radius is small compared to the other dimensions of practical interest, a well can conveniently be idealized as a mathematical sink. As the sink is approached, the gradient increases in such fashion that

$$2\pi T r\,(\partial s/\partial r) = -Q$$

Q being the discharge of the well and r being measured from the center of the well.

Problem 1, infinite plane--In this problem the steadily discharging well draws its water from vertical leakage into an infinite plane aquifer. The drawdown at infinity is zero. It is shown [JACOB, 1946; HANTUSH, 1949] that the solution for this case is given by

$$s/(Q/2\pi T) = K_0\,(r/B) = K_0\left[(1/B)\sqrt{(x-x_1)^2+(y-y_1)^2}\right]$$

where K_0 is the modified Bersel's function of the second kind of zero order, and where the center of the well is at the point (x_1, y_1). The distance r is measured from the center of the well.

It is easily shown that any linear combination of $K_0\,(r/B)$ has the first three properties of the Green's function. Due to the linearity and homogeneity of the steady-state differential equation, the fourth property can be established for several regions of different geometrical forms by application of the method of images as outlined above. From this one concludes that the head distribution produced by a steadily discharging well situated in a region whose boundaries are kept at constant head or at zero flux is approximately the Green's function of that region, except for a constant value. In fact, this constant is the value of the constant head specified on the boundary. Hence the solutions in which the drawdown, the flux, or both vanish on the boundary of the region will be the Green's function of the region with the corresponding conditions over its boundary.

The Green's function for the infinite plane is, therefore

$$G'(x, y; x_1, y_1) = K_0\left[(1/B)\sqrt{(x-x_1)^2+(y-y_1)^2}\right]$$

Problem 2, infinite half-plane--Two cases may arise in considering the flow induced by a steadily discharging well situated in an infinite half-plane: (1) The well is situated near a fairly straight stretch of a river or a canal. The stream may represent a straight-line boundary along

which the head is constant. (2) The well is situated near a fairly straight stretch of a buried bedrock wall or fault. The latter may represent a straight-line boundary across which the flux is zero.

The two cases are shown schematically in Figure 3a.

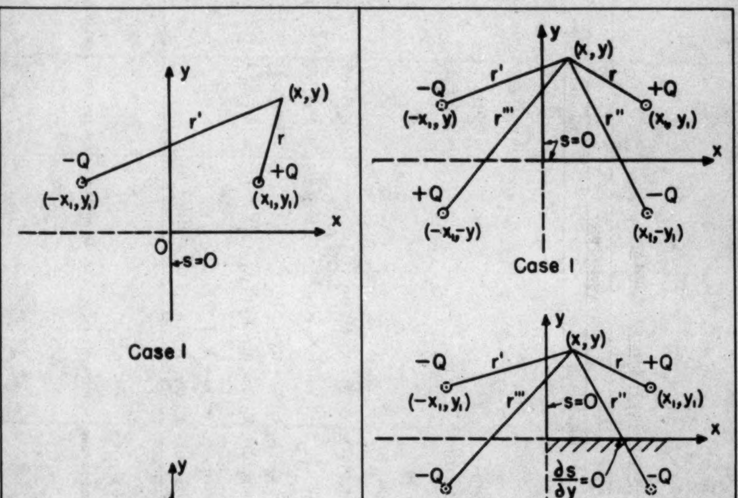
y
(x, y)
r'
r
-Q
+Q
(-x₁, y₁)
(x₁, y₁)
x
O
s=O
Case I
y
r'
r
-Q
+Q
(-x₁, y₁)
(x₁, y₁)
x
∂s/∂x=O
(a)
Case 2
y
(x, y)
r'
r
-Q
+Q
(-x₁, y)
(x₁, y₁)
r'''
r''
s=O
x
+Q
-Q
(-x₁,-y)
(x₁,-y₁)
Case I
y
(x, y)
-Q
r'
r
+Q
(-x₁, y₁)
r'''
s=O
r''
(x₁, y₁)
x
-Q
∂s/∂y=O
-Q
(-x₁,-y₁)
(x₁,-y₁)
Case 2
y
∂s/∂x=O
(x, y)
r'
r
Q
Q
(-x₁, y₁)
(x₁, y₁)
r'''
r''
x
+Q
∂s/∂y=O
-Q
(-x₁,-y)
(x₁,-y)
(b)
Case 3

Fig. 3--Image systems for (a) the cases of the infinite half-plane which gives the required drawdown distribution; (b) the infinite quadrant

Table 1--Solutions of Problems 1, 2, and 3

Shape of region	Case		Type of aquifer	
			Leaky systems	Non-leaky systems
Infinite plane		$s/(Q/2\pi T)$	$K_0\ (r/B)$	$\ln\ (r_e/r)$
		$s_w/(Q/2\pi T)$	$K_0\ (r_w/B)$	$\ln\ (r_e/r_w)$
Infinite half-plane	Case 1	$s/(Q/2\pi T)$	$K_0\ (r/B) - K_0\ (r'/B)$	$\ln\ (r'/r)$
		$s_w/(Q/2\pi T)$	$K_0\ (r_w/B) - K_0\ (2x_1/B)$	$\ln\ (2x_1/r_w)$
	Case 2	$s/(Q/2\pi T)$	$K_0\ (r/B) + K_0\ (r'/B)$	. . .
		$s_w/(Q/2\pi T)$	$K_0\ (r_w/B) + K_0\ (2x_1/B)$	. . .
Infinite quadrant	Case 1	$s/(Q/2\pi T)$	$K_0\ (r/B) + K_0\ (r'''/B) - K_0\ (r'/B) - K_0\ (r''/B)$	$\ln\ (r'r''/rr''')$
		$s_w/(Q/2\pi T)$	$K_0\ (r_w/B) + K_0\ [2\ (x_1^2 + y_1^2)^{1/2}/B] - K_0\ (2y_1/B) - K_0\ (2x_1/B)$	$\ln\ [2x_1y_1/r_w\ (x_1^2 + y_1^2)^{1/2}]$
	Case 2	$s/(Q/2\pi T)$	$K_0\ (r/B) + K_0\ (r'/B) - K_0\ (r''/B) - K_0\ (r'''/B)$	$\ln\ (r''r'''/rr')$
		$s_w/(Q/2\pi T)$	$K_0\ (r_w/B) + K_0\ (2x_1/B) - K_0\ (2y_1/B) - K_0\ [2\ (x_1^2 + y_1^2)^{1/2}/B]$	$\ln\ [2y_1\ (x_1^2 + y_1^2)^{1/2}/x_1r_w]$
	Case 3	$s/(Q/2\pi T)$	$K_0\ (r/B) + K_0\ (r'/B) + K_0\ (r''/B) + K_0\ (r'''/B)$	. . .
		$s_w/(Q/2\pi T)$	$K_0\ (r_w/B) + K_0\ (2x_1/B) + K_0\ (2y_1/B) + K_0\ [2\ (x_1^2 + y_1^2)^{1/2}/B]$	. . .

$r^2 = (x - x_1)^2 + (y - y_1)^2$, $r'^2 = (x + x_1)^2 + (y - y_1)^2$

$r''^2 = (x - x_1)^2 + (y + y_1)^2$ and $r'''^2 = (x + x_1)^2 + (y + y_1)^2$

r_e is the effective radius to the outer boundary and is taken arbitrarily large. The Green's function for each region is given by $s/(Q/2\pi T)$.

Problem 3, infinite quadrant--Three cases arise in which either the drawdown, the flux, or both vanish on the boundaries in considering the flow into a steadily discharging well situated in an infinite quadrant. Let the boundaries be represented by the x- and y-axis and let the center of the well be at the point (x_1, y_1) as shown in Figure 3b. Then the three cases are:

(1) $s(0, y) = 0$ and $s(x, 0) = 0$ for Figure 3b, Case 1. This system corresponds to the flow to a well situated near a right-angle bend in a stream or between two rivers or canals that meet at right angles.

(2) $s(0, y) = 0$ and $[\partial s(x, 0)/\partial y] = 0$ for Figure 3b, Case 2. This system may represent the flow to a well located near a buried bedrock wall that cut across a stream.

(3) $[\partial s(0, y)/\partial x] = 0$ and $[\partial s(x, 0)/\partial y] = 0$ for Figure 3b, Case 3. This may correspond to the flow to a well situated between two impermeable boundaries at right angle to each other. The boundaries may be two faults, two bedrock walls, or one of each.

The solutions of the above mentioned problems in leaky systems and the corresponding solutions for non-leaky systems are tabulated in Table 1. They are obtained simply by applying the method of images as outlined above. The image system for each case is shown clearly in Figure 3.

The drawdown at the face of the well s_w is obtained in each case by letting the point (x, y) be at the well surface, in which case r is equal to r_w and the distances r', r'', and r''' will very closely be equal to $2x_1$, $2y_1$, and $2\sqrt{x_1^2 + y_1^2}$, respectively.

The solutions to the systems of non-leaky aquifers are obtained from the corresponding solutions for the leaky systems by letting the leakage (K'/b') and hence $(1/B)$ approach zero. It should be remembered also that, for small values of x, $K_0(x) = -\gamma - \ln(x/2)$ where γ is Euler's constant, equals 0.577216.

The drawdown distribution for the flow into a well from an infinite line source at uniform head (Problem 2, Case 1) is shown in Figure 4 for $(x_1/B) = 1$. The corresponding distribution for zero leakage is given in Figure 5.

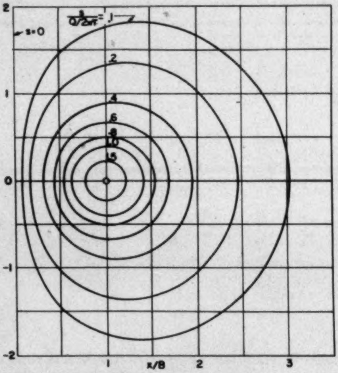

Fig. 4--Drawdown distribution curves for the flow into a well from an infinite line source at uniform head with $(x_1/B) = 1$

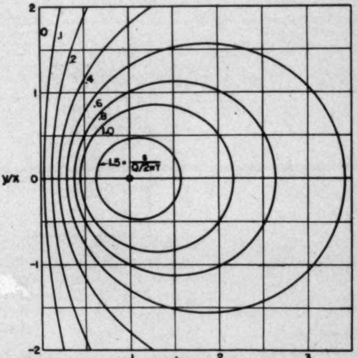

Fig. 5--Drawdown distribution curves for the flow into a well from an infinite line source at uniform head if leakage is zero

Figure 6 gives the drawdown distribution in a quadrant (Problem 3, Case 1) due to a well whose center is on the line $y_1 = x_1$, with $(x_1/B) = 1$. For detailed discussion on the construction of Figures 4, 5, 6, and 7, one is referred to HANTUSH [1949].

The drawdown at the face of the well for the different cases presented above can be found by use of Figure 7 for various values of (r_w/B), (y_1/B), and of (x_1/B).

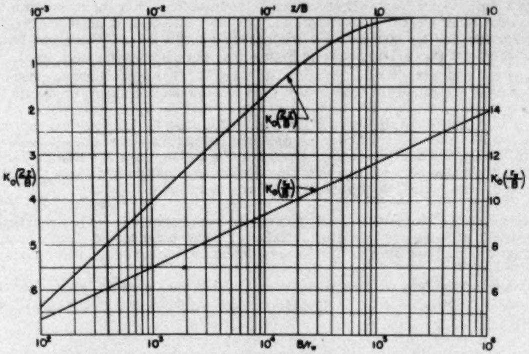

Fig. 6--Drawdown at well face for the different cases of the infinite plane, the infinite half-plane, and the infinite quadrant

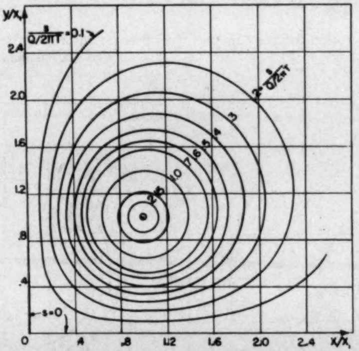

Fig. 7--Drawdown distribution curves for the flow into a well from two perpendicular line sources with $x_1/B = 1$; the line sources are kept at uniform head

PART II

Analysis: Problem 4, infinite strip--Three cases in which either the drawdown, the flux, or both vanish on the boundaries arise in considering the flow to a steadily discharging well in an infinite strip. These are diagramatically shown in Figure 8. Let the boundaries of the infinite strip be the lines $x = \pm a$ in the xy-plane, and let the center of the well be at the point (x_1, y_1) as shown in Figure 8. Then the three cases are:

(1) $s(\pm a, y) = 0$, Figure 8, Case 1. This system corresponds to the flow to a well located between two parallel rivers or canals. The latter may simulate straight-line boundaries along which the head is essentially uniform, assuming the streams to be of large capacity and to have small slopes.

(2) $s(a, y) = 0$ and $(\partial s/\partial x)(0, y) = 0$, Figure 8, Case 2. This system is a combination of Case 1 and Case 3.

(3) $(\partial s/\partial x)(\pm a, y) = 0$, Figure 8, Case 3. This system corresponds to the flow to a well in a region whose boundaries are impermeable. They may be two parallel faults or buried bedrock walls or ledges.

The solutions to the above cases will be built up from the solution for the infinite plane by applying the method of images.

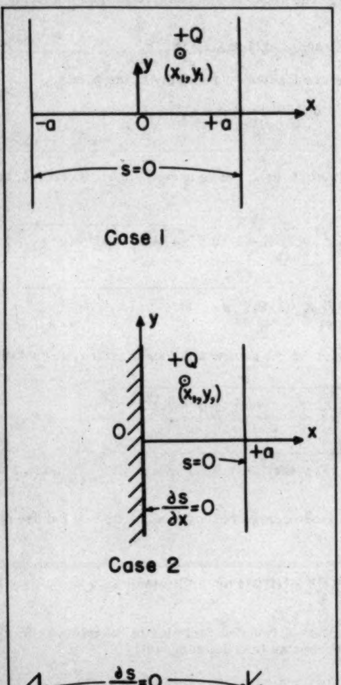
+Q
(x_1, y_1)
y
x
-a
0
+a
s=0
Case 1
y
+Q
(x_1, y_1)
0
x
+a
s=0
$\frac{\partial s}{\partial x}=0$
Case 2
$\frac{\partial s}{\partial x}=0$
+Q
(x_1, y_1)
y
x
-a
0
+a
Case 3

Fig. 8--Diagramatic representation for the three cases of the infinite strip

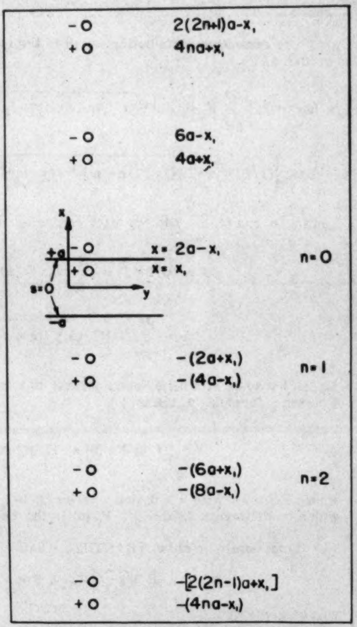
- o
+ o
$2(2n+1)a-x_1$
$4na+x_1$
- o
+ o
$6a-x_1$
$4a+x_1$
x
+a
- o
+ o
x = $2a-x_1$
x = x_1
s=0
y
-a
n=0
- o
+ o
$-(2a+x_1)$
$-(4a-x_1)$
n=1
- o
+ o
$-(6a+x_1)$
$-(8a-x_1)$
n=2
- o
+ o
$-[2(2n-1)a+x_1]$
$-(4na-x_1)$

Fig. 9--Image system which gives zero drawdown along $x = \pm a$, with the well at (x_1, y_1); the images extend to ∞; discharging wells (sinks) and recharging wells (sources) are indicated by + and - signs respectively

Case 1--A vanishing drawdown over the boundary $x = a$, Figure 9, can be obtained by setting up a negative image of the actual well at $(2a - x_1, y_1)$. If the negative images of these two wells are put at $[-(2a + x_1), y_1]$ and $[-(4a - x_1), y_1]$, respectively, the drawdown on the boundary, $x = -a$, will be zero. However, the latter two images will cause a non-vanishing drawdown over $x = a$, and hence their negative images must be set up at $[(4a + x_1), y_1]$ and $[(6a - x_1), y_1]$, respectively. This process must be continued infinitely many times, as a result of which an infinite line of positive and negative images will be parallel to the x-axis. The negative and positive images above the y-axis are located respectively at the points.

$$\left\{[2\,(2n + 1)\,a - x_1], y_1\right\} \qquad \text{and} \qquad [(4na + x_1), y_1]$$

where $n = 0, 1, 2, \ldots$, and those below the y-axis are located respectively at the points

$$\left\{-[2\,(2n - 1)\,a + x_1], y_1\right\} \qquad \text{and} \qquad [-(4na - x_1), y_1]$$

where $n = 1, 2, 3, \ldots$.

The drawdown distribution which is the resultant of these image systems may, therefore, be written as

$$s/(Q/2\pi T) = \sum_{n=0}^{\infty} K_0\left\{(1/B)\sqrt{[x - (4na + x_1)]^2 + (y - y_1)^2}\right\} + \sum_{n=1}^{\infty} K_0\left\{(1/B)\sqrt{[x + (4na - x_1)]^2 + (y - y_1)^2}\right\}$$

$$- \sum_{n=0}^{\infty} K_0\left\{(1/B)\sqrt{\{x - [2\,(2n + 1)\,a - x_1]\}^2 + (y - y_1)^2}\right\} - \sum_{n=1}^{\infty} K_0\left\{(1/B)\sqrt{[x + 2\,(2n - 1)\,a + x_1]^2 + (y - y_2)^2}\right\}$$

Letting n run from -1 to $-\infty$ after replacing n by $-n$ in the second and fourth series, one obtains

$$s/(Q/2\pi T) = \sum_{-\infty}^{\infty} K_0\left\{(1/B)\sqrt{[(x - x_1) - 4na]^2 + (y - y_1)^2}\right\}$$

$$- \sum_{-\infty}^{\infty} K_0\left\{(1/B)\sqrt{[(x + x_1 - 2a) - 4na]^2 + (y - y_1)^2}\right\} \ldots\ldots\ldots\ldots\ldots (13)$$

Eq. (13) may be simplified considerably to a form more convenient for computation by the use of Poisson's formula, which is

$$\sqrt{\beta}\,\left[(1/2)\,F_c\,(0) + \sum_{n=1}^{\infty} F_c\,(n\beta)\right] = \sqrt{\theta}\,\left[(1/2)\,f\,(0) + \sum_{n=1}^{\infty} f\,(n\theta)\right] \ldots\ldots\ldots\ldots (14)$$

where $\theta\beta = 2\pi$ with $\theta > 0$, and where $f(u)$ is a function of bounded variation in the interval $(0, \infty)$ which tends to zero as $u \rightarrow \infty$. $F_c(u)$ is the Fourier-cosine transform of $f(u)$.

It can easily be shown [HANTUSH, 1949] that the function whose cosine transform

$$F_c\,(t) = (1/\sqrt{2\pi})\left\{K_0[Z\sqrt{(b + t)^2 + C^2}] + K_0[Z\sqrt{(b - t)^2 + C^2}]\right\}$$

will be given by

$$f\,(\alpha) = \frac{\exp\,(-C\sqrt{\alpha^2 + Z^2})}{\sqrt{\alpha^2 + Z^2}}\cos\alpha b$$

If $f(\alpha)$ and $F_c(t)$ are substituted in Poisson's formula and if β and θ are taken equal to 1 and 2π respectively, after algebraic simplification one obtains

$$\sum_{-\infty}^{\infty} K_0[Z\sqrt{(b-n)^2 + C^2}] = (\pi/Z)\exp(-CZ) + 2\pi\sum_{n=1}^{\infty}\frac{\exp[-C\sqrt{(2n\pi)^2 + Z^2}]}{\sqrt{(2n\pi)^2 + Z^2}}\cos 2n\pi b \ldots\ldots (15)$$

Choosing the values $Z = (4a/B)$, $b = (|x - x_1|/4a)$, and $C = (|y - y_1|/4a)$ (15) becomes

$$\sum_{-\infty}^{\infty} K_0\left\{(1/B)\sqrt{[(x - x_1) - 4na]^2 + (y - y_1)^2}\right\} = \frac{1}{2}\,\frac{\exp(-|y - y_1|/B)}{(2a/\pi B)}$$

$$+ \sum_{n=1}^{\infty} \frac{\exp[-(\pi/2a)|y - y_1|\sqrt{n^2 + (2a/\pi B)^2}]}{\sqrt{n^2 + (2a/\pi B)^2}} \cos(n\pi/2a)(x - x_1) \; \ldots\ldots\ldots \quad (16)$$

Similarly for $Z = (4a/B)$, $b = (|x + x_1 - 2a|/4a)$, and $C = (|y - y_1|/4a)$ (15) reduces to

$$\sum_{-\infty}^{\infty} K_0\left\{(1/B)\sqrt{[(x + x_1 - 2a) - 4na]^2 + (y - y_1)^2}\right\} = \frac{1}{2}\,\frac{\exp(-|y - y_1|/B)}{(2a/\pi B)}$$

$$+ \sum_{n=1}^{\infty} \frac{\exp[-(\pi/2a)|y - y_1|\sqrt{n^2 + (2a/\pi B)^2}]}{\sqrt{n^2 + (2a/\pi B)^2}} \cos(n\pi/2a)(x + x_1 - 2a) \; \ldots\ldots\ldots \quad (17)$$

Subtracting (17) from (16), the left-hand member of the resulting equation will be seen to be identical to the right-hand member of (13), which is equal to $s/(Q/2\pi T)$ and hence

$$s/(Q/2\pi T) = \sum_{n=1}^{\infty} \frac{\exp[-(\pi/2a)|y-y_1|\sqrt{n^2+(2a/\pi B)^2}]}{\sqrt{n^2 + (2a/\pi B)^2}}[\cos(n\pi/2a)(x - x_1) - \cos(n\pi/2a)(x + x_1 - 2a)] \; \ldots\ldots\ldots \quad (18)$$

or

$$G'(x,y;x_1,y_1) = 2\sum_{n=1}^{\infty} \frac{\exp[-(\pi/2a)|y - y_1|\sqrt{n^2+(2a/\pi B)^2}]}{\sqrt{n^2 + (2a/\pi B)^2}} \sin(n\pi/2a)(x - a)\sin(n\pi/2a)(x_1 - a) \; \ldots\ldots\ldots \quad (19)$$

It may be shown [HANTUSH, 1949] that this series is uniformly convergent at all points in the infinite strip except at the center of the well. Eq. (19) gives the Green's function for Case 1 of the infinite strip.

Approximate solution--For small values of $(|y - y_1|/a)$ the series (19) converges very slowly and computation of the potential at such points becomes very laborious. An approximate solution, yet very useful one for computations whenever $(|y - y_1|/a)$ is small, will now be developed.

Henceforth the expressions $\sqrt{n^2 + (2a/\pi B)^2}$ and $[\cos(n\pi/2a)(x - x_1) - \cos(n\pi/2a)(x + x_1 - 2a)$, which is equal to $[\cos(n\pi/2a)(x - x_1) - (-1)^n\cos(n\pi/2a)(x + x_1)] = 2\sin(n\pi/2a)(x - a)\sin(n\pi/2a)(x_1 - a)$, will be denoted by δ and γ respectively. Using this notation (18) can be approximated by

$$s/(Q/2\pi T) \approx \sum_{n=1}^{N} (\gamma/\delta)\exp[-(\pi\delta/2a)|y - y_1|] + \sum_{n=n+1}^{\infty} (\gamma/n)\exp[-(n\pi/2a)|y - y_1|] \ldots \quad (20)$$

where N is a positive integer large enough so that δ can be approximated by n.

Adding and subtracting the sum $\sum_{n=1}^{N} (\gamma/n)\exp[-(n\pi/2a)|y - y_1|]$ (20) becomes

$$s/(Q/2\pi T) \approx \sum_{n=1}^{\infty} (\gamma/n)\exp[-(n\pi/2a)|y - y_1|]$$

$$+ \sum_{n=1}^{N} \gamma\left\{(1/\delta)\exp[-(\pi\delta/2a)|y - y_1|] - (1/n)\exp[-(n\pi/2a)|y - y_1|]\right\} \;\ldots \quad (21)$$

The first sum in (21) is shown [HANTUSH, 1949] to be

$$\sum_{n=1}^{\infty} (\gamma/n) \exp\left[-(n\pi/2a)\left|y - y_1\right|\right] = (1/2) \ln \left[\frac{\cosh(\pi/2a)(y - y_1) + \cos(\pi/2a)(x + x_1)}{\cosh(\pi/2a)(y - y_1) - \cos(\pi/2a)(x - x_1)}\right] \quad \ldots (22)$$

Hence the final form of the approximate solution is obtained by substituting (22) in (21).

Drawdown distribution curves for two locations of the center of a well, namely, $[(a/2), 0]$ and $(0, 0)$ are shown in Figures 10 and 11 respectively with $a/B = \pi/2$.

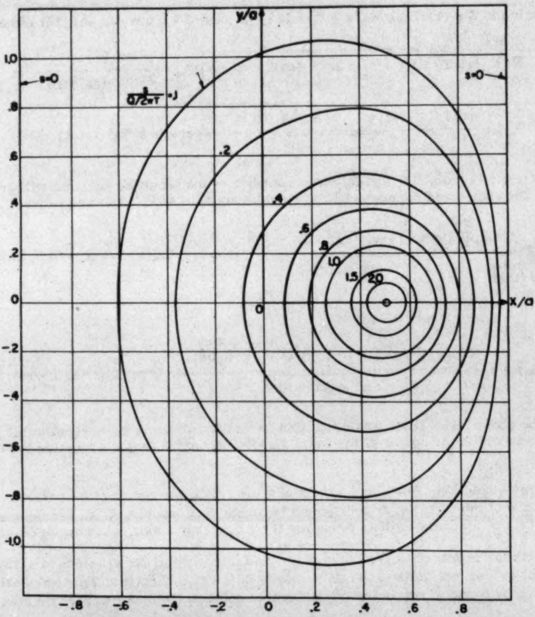

Fig. 10--Drawdown distribution curves (infinite strip Case 1) for the flow to a well whose center is at $(a/2, 0)$ with $a/B = \pi/2$

Green's function for non-leaky system--The Green's function for an infinite strip of non-leaky aquifer [MUSKAT, 1937] is

$$G(x, y; x_1, y_1) = (1/2) \ln \left[\frac{\cosh(\pi/2a)(y - y_1) + \cos(\pi/2a)(x + x_1)}{\cosh(\pi/2a)(y - y_1) - \cos(\pi/2a)(x - x_1)}\right] \quad \ldots\ldots\ldots (23)$$

Eq. (23) can be developed from the solution given by (18) by letting the leakage $1/B$ approach zero [HANTUSH, 1949].

Drawdown at the face of the well--At the face of the well $y - y_1 = 0$, $x - x_1 = r_w$, and $x + x = 2x_1$. For these values (18) gives

$$s_w/(Q/2\pi T) = \sum_{n=1}^{\infty} \frac{[\cos(n\pi/2a)\, r_w - (-1)^n \cos(n\pi/a)\, x_1]}{\sqrt{n^2 + (2a/\pi B)^2}} \quad \ldots\ldots\ldots\ldots (24)$$

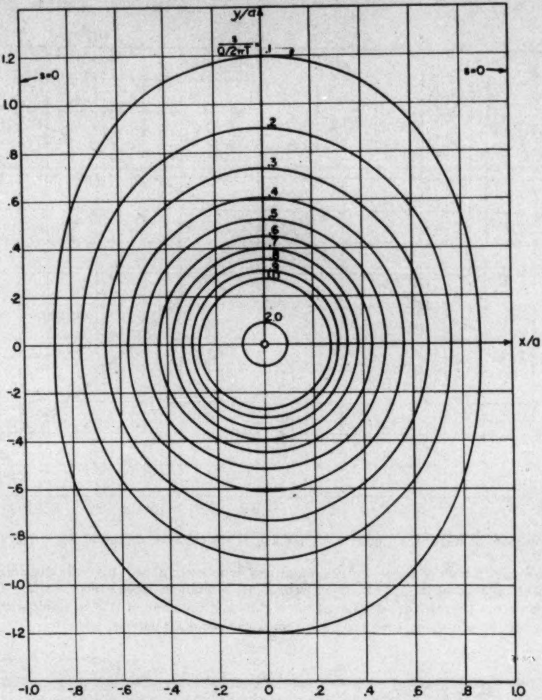

Fig. 11--Drawdown distribution curves (infinite strip Case 1) for the flow to a well whose center is at (0, 0) with $a/B = \pi/2$

and the approximate value by (22) is

$$s_w/(Q/2\pi T) \approx (1/2)\ln\left[\frac{1+\cos(\pi/a)\,x_1}{1-\cos(\pi/2a)\,r_w}\right] + \sum_{n=1}^{N}\left[(1/\delta)-(1/n)\right]\left[\cos(n\pi/2a)\,r_w-(-1)^n\cos(n\pi/a)\,x_1\right] \qquad (25)$$

where N is large enough that $\left\{\left[1/\sqrt{n^2+(2a/\pi B)^2}\right]-(1/n)\right\}$ becomes very small.

Figure 12 gives the drawdown at the face of the well for various values of x_1/a, a/B, and of r_w/a. The two functions shown in Figure 12 are related to s_w by

$$s_w/(Q/2\pi T) = f(r_w/a) - g(a/B, x_1/a) \qquad (26)$$

Case 2--If the system of images set up in Case 1 is reflected positively in the y-axis, that is, if another well is supposed to exist at $(-x_1, y_1)$, then there will be no flow across the y-axis.

The drawdown produced by an actual well with center at (x_1, y_1) is given by (19), and that produced by an hypothetical well with center at $(-x_1, y_1)$ is given by (19) with the sign of x_1 reversed.

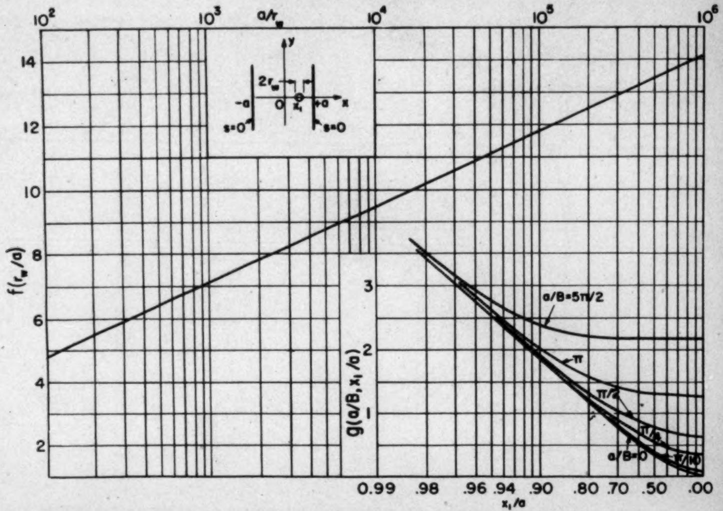

Fig. 12--Drawdown at well face (infinite strip Case 1) for various values of x_1/a, r_w/a, and of a/B

The drawdown due to both of these wells (actual and hypothetical) will give the drawdown produced by a single well, placed at (x_1, y_1) in an infinite strip of width a whose left boundary (Fig. 1, Case 2) is impermeable. Therefore, addition of the right-hand member of (19) to itself with x_1 replaced by $-x_1$ will, after simplication, give the required drawdown distribution, which is

$$s/(Q/2\pi T) = G'(x, y; x_1, y_1) = 4 \sum_{n=1}^{\infty} (-1)^n \frac{\exp\left[-(\pi/2a)\,|y - y_1|\,\sqrt{(2n-1)^2 + (2a/\pi B)^2}\right]}{\sqrt{(2n-1)^2 + (2a/\pi B)^2}}$$

$$\times \sin\left[(2n-1)\,\pi/2a\right](x - a)\,\cos\left[(2n-1)\,\pi/2a\right] x_1 \quad \ldots\ldots\ldots (27)$$

Non-leaky system--If there were no leakage, the drawdown distribution, and hence the Green's function for this case would be obtained by adding to (23) the equation resulting from it after replacing x_1 by $-x_1$.

Case 3--To obtain a vanishing flux across the boundaries $x = \pm a$ the images obtained in Case 1 should all be positive; and, therefore, the series of K_0 in (13) should be added. This in turn leads to the addition of the right-hand sides of (16) and (17) and hence, after simplification

$$s/(Q/2\pi T) = G'(x, y; x_1, y_1) = (\pi B/2a) \exp(-|y - y_1|/B)$$

$$+ 2 \sum_{n=1}^{\infty} (1/\delta) \exp\left[-(\pi\delta/2a)\,|y - y_1|\right] \cos(n\pi/2a)(x - a) \cos(n\pi/2a)(x_1 - a) \quad \ldots (28)$$

where, as before, $\delta = \sqrt{n^2 + (2a/\pi B)^2}$.

Non-leaky system--If the leakage vanishes or $1/B \rightarrow 0$, then (28) will reduce to [HANTUSH, 1949]

$$G(x, y; x_1, y_1) = -(1/2)\ln[\cosh(\pi/2a)(y - y_1) + \cos(\pi/2a)(x + x_1)] \times [\cosh(\pi/2a)(y - y_1) - \cos(\pi/2a)(x - x_1)] \quad \text{.............. (29)}$$

It is noted here that by using l'Hopital rule of limits, $\lim_{B \to \infty} [1/(2a/\pi B)] \times \exp(-|y - y_1|/B)$ is equal to $(-\pi|y - y_1|/2a)$.

Problem 5, infinite half-strip--Six problems in which the drawdown, the flux, or both vanish on the boundaries may be considered when the flow is induced by a steadily discharging well, in an infinite half-strip. Two of these problems are of special practical interest. The other four are of less frequent occurrence in nature. However, since they are of mathematical interest, their solutions will be developed.

In Figure 13 let the lines $x = \pm a$ represent the infinite boundaries and let the line $y = 0$ be the third boundary. Then the six problems may be classified as follows:

(1) $s(\pm a, y) = 0$ and $s(x, 0) = 0$, Figure 13, Case 1. This problem may correspond to the flow into a well located between two parallel canals with a stream at right angles to them.

(2) $(\partial s/\partial x)(0, y) = 0$, $s(x, 0) = 0$, and $s(a, y) = 0$, Figure 13, Case 2.

(3) $(\partial s/\partial x)(0, y) = 0$, $(\partial s/\partial y)(x, 0) = 0$, and $s(a, y) = 0$, Figure 13, Case 3.

(4) $(\partial s/\partial x)(\pm a, y) = 0$ and $s(x, 0) = 0$, Figure 13, Case 4. A special case of this problem of great practical importance. If the well is at the center line of the infinite half-strip, the problem may correspond to the flow to an infinite line of wells, equally spaced, and parallel to a straight stretch of a river bank. Such systems of wells may be used to relieve the pressure under dams or levees.

(5) $s(\pm a, y) = 0$ and $(\partial s/\partial y)(x, 0) = 0$, Figure 13, Case 5.

(6) $(\partial s/\partial x)(\pm a, y) = 0$ and $(\partial s/\partial y)(x, 0) = 0$, Figure 13, Case 6.

The solutions of Problem 4, for an infinite strip, will be used in developing the solutions for the different cases of the present problem.

Case 1--If a negative image of the actual well in Case 1 of the infinite strip is assumed to exist below the x-axis, the drawdown on the x-axis will vanish; and, therefore, the solution of this case is the sum of two solutions of Problem 4, Case 1, one for a well at (x_1, y_1), and the other for a well at $(x_1, -y_1)$. Adding the right-hand side of (19) to the negative of the right-hand side of the equation resulting from it by replacing y_1 by $-y_1$, the drawdown will be given by

$$s/(Q/2\pi T) = G'(x, y; x_1, y_1) = 2\sum_{n=1}^{\infty} (1/\delta)\Big\{\exp[-(\pi/2a)|y - y_1|\delta] - \exp[-(\pi/2a)|y + y_1|\delta]\Big\} \sin(n\pi/2a)(x - a)\sin(n\pi/2a)(x_1 - a) \quad \text{....... (30)}$$

By a similar process, from (23) the drawdown for a non-leaky system will be

$$s/(Q/2\pi T) = G(x, y; x_1, y_1) = (1/2)\ln\Big[\frac{\cosh(\pi/2a)(y - y_1) + \cos(\pi/2a)(x + x_1)}{\cosh(\pi/2a)(y - y_1) - \cos(\pi/2a)(x - x_1)}\Big] \times \Big[\frac{\cosh(\pi/2a)(y + y_1) - \cos(\pi/2a)(x - x_1)}{\cosh(\pi/2a)(y + y_1) + \cos(\pi/2a)(x + x_1)}\Big] \quad \text{.................... (31)}$$

Drawdown at face of well--Letting $y = y_1$ and $x - x_1 = r_w$, (30) reduces to

$$s_w/(Q/2\pi T) = \sum_{n=1}^{\infty} (1/\delta)[\cos(n\pi/2a)r_w - (-1)^n\cos(n\pi/a)x_1]\Big\{1 - \exp[-(\pi/a)|y_1|\delta]\Big\} \quad \text{..... (32)}$$

in which the sum which does not contain the exponential factor gives the drawdown at the well face for the infinite strip, Case 1. The remaining series is rapidly convergent. Thus, computations are reduced considerably, once the drawdown for the infinite strip, Case 1, is known (see Fig. 12).

Case 2--If there are two wells in Case 2 of the infinite strip, one of positive discharge at (x_1, y_1) and the other of negative discharge at $(x_1, -y_1)$, then the drawdown produced by them will correspond to that due to a single well at (x_1, y_1) in the infinite half-strip with vanishing drawdown on

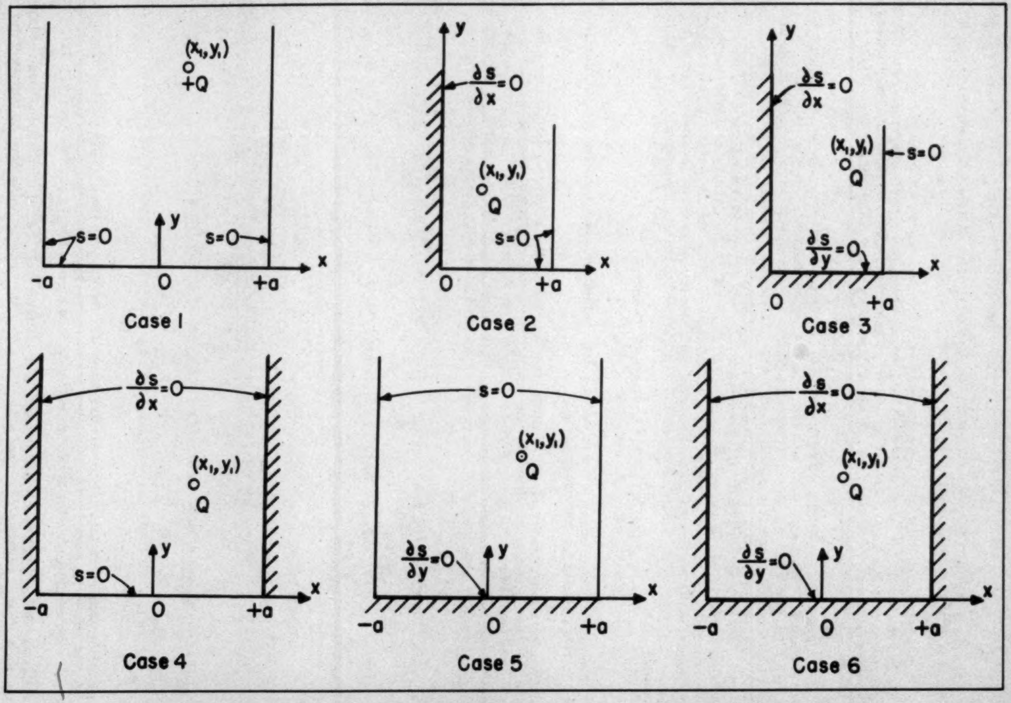
(x_1, y_1)
+Q
s=0
s=0
y
x
-a
0
+a
Case 1
y
$\frac{\partial s}{\partial x}=0$
(x_1, y_1)
Q
s=0
x
0
+a
Case 2
y
$\frac{\partial s}{\partial x}=0$
(x_1, y_1)
Q
s=0
$\frac{\partial s}{\partial y}=0$
x
0
+a
Case 3
$\frac{\partial s}{\partial x}=0$
(x_1, y_1)
Q
s=0
y
x
-a
0
+a
Case 4
s=0
(x_1, y_1)
Q
$\frac{\partial s}{\partial y}=0$
y
x
-a
0
+a
Case 5
$\frac{\partial s}{\partial x}=0$
(x_1, y_1)
Q
$\frac{\partial s}{\partial y}=0$
y
x
-a
0
+a
Case 6

Fig. 13--Diagramatic representation for the six cases of the infinite half-strip

the x-axis. Thus the solution to the present case can be obtained by subtracting the right-hand side of (27) with the sign of y_1 reversed from (27) proper.

The corresponding solution, for a non-leaky system, can similarly be obtained by using the corresponding solutions in the infinite strip.

Case 3--A vanishing flux across the x-axis will be obtained by adding (27) to itself with y_1 replaced by $-y_1$. By a similar procedure the solution for a non-leaky system can be obtained, using instead the corresponding solution in the infinite strip.

Case 4--If the drawdown distribution due to a well in Case 3 of the infinite strip and that due to its negative image below the x-axis are added together, then a zero drawdown over the x-axis will be obtained. Therefore, by (28) the drawdown distribution for the present case will be

$$\begin{aligned} s/(Q/2\pi T) = G'(x, y; x_1, y_1) = (\pi B/2a)\ [\exp(-|y-y_1|/B) \\ - \exp(-|y+y_1|/B)] + 2\sum_{n=1}^{\infty}(1/\delta)\left\{\exp[-(\pi/2a)\,|y-y_1|\,\delta]\right. \\ \left.- \exp[-(\pi/2a)\,|y+y_1|\,\delta]\right\}\cos(n\pi/2a)(x-a)\cos(n\pi/2a)(x_1-a) \quad \ldots\ldots (33) \end{aligned}$$

By a similar process, from (29) the corresponding solution for the non-leaky case will be

$$\begin{aligned} s/(Q/2\pi T) = G(x, y; x_1, y_1) = (1/2)\ \ln\left[\frac{\cosh(\pi/2a)(y+y_1) + \cos(\pi/2a)(x+x_1)}{\cosh(\pi/2a)(y-y_1) + \cos(\pi/2a)(x+x_1)}\right] \\ \times \left[\frac{\cosh(\pi/2a)(y+y_1) - \cos(\pi/2a)(x-x_1)}{\cosh(\pi/2a)(y-y_1) - \cos(\pi/2a)(x-x_1)}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (34) \end{aligned}$$

Drawdown at the well face--Putting $y = y_1$ and $x - x_1 = r_w$ in (33) and simplifying, the drawdown at the well face will be

$$\begin{aligned} s_w/(Q/2\pi T) = (\pi B/2a)\ [1 - \exp(-2|y_1|/B)] \\ + \sum_{n=1}^{\infty}(1/\delta)\,[\cos(n\pi/2a)\,r_w + (-1)^n\cos(n\pi/a)\,x_1]\left\{1 - \exp[-(\pi/a)|y_1|\,\delta]\right\} \ldots\ldots (35) \end{aligned}$$

The terms which do not have the exponential functions as a factor in the above equation give the drawdown at the face of a well in the corresponding infinite strip.

The drawdown at the well face for various values of y_1/a, r_w/a, and of a/B is given in Figure 14 for a well located in the middle of the infinite half-strip. The two functions shown in Figure 14 are related to s_w by the following equation

$$s_w/(Q/2\pi T) = f_3\,(r_w/a) - g_3\,(a/B,\ y_1/a)$$

Case 5--The solution for this case will correspond to the solution for Case 1 of the infinite strip, if, instead of one well, there exist two wells, one at (x_1, y_1) and the other at $(x_1, -y_1)$, for then the flux across the x-axis will vanish. The drawdown distribution due to these two wells in the infinite strip will be that due to one well in the infinite half-strip.

The solution for a non-leaky system will similarly be obtained by starting with (23).

Case 6--Had there existed another well of positive discharge below the x-axis at $(x_1, -y_1)$ in Case 3 of the infinite strip, the flux across the x-axis would again have been zero; and, therefore, the boundary conditions in the present case would have been satisfied. Thus, summing up the solutions due to two wells in Case 3 of the infinite strip, one at (x_1, y_1) and the other at $(x_1, -y_1)$, the drawdown distribution for the present case will be obtained.

Problem 6, rectangle--The solution of the problem of a steadily discharging well situated in a region whose boundaries may be simulated by the sides of a rectangle will now be developed. The six cases which may arise in such a problem are shown in Figure 15.

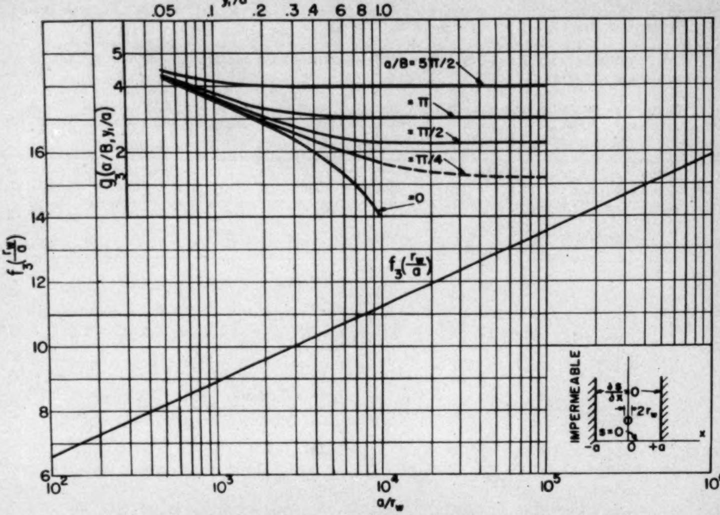

Fig. 14--Drawdown at well face (infinite half-strip Case 4) for various values of y_1/a, r_w/a, and of a/b with well at $(0, y_1)$

Case 1: $s(\pm a, y) = 0$ and $s(x, \pm b) = 0$, Figure 15--By starting with the solution for Case 1 of the infinite strip and by setting up the appropriate system of images (compare Case 1 of the infinite strip) the drawdown on the boundaries $y = \pm b$ can be made to vanish. If the well which, together with its family of images, produce zero drawdown over the boundaries $x = \pm a$ is located at (x_1, y_1) within the infinite strip, then the positive and negative wells above the x-axis, and the positive and negative wells below the x-axis, which will combine to give a vanishing drawdown over the other boundaries $y = \pm b$, are located at the points whose common absissa is x_1 and whose ordinates are respectively

$$\left\{[(4mb + y_1)], [2\,(2m + 1)\,b - y_1], \; m = 0, 1, 2, 3, \ldots\right\}$$

and

$$\left\{-\,(4mb - y_1), -\,[2\,(2m - 1)\,b + y_1], \; m = 1, 2, 3, \ldots\right\}$$

Thus, the drawdown distribution due to this infinite line of wells will be obtained by replacing y_1 of (19) by the corresponding ordinate for each image of the infinite line of images and summing up the result. The resulting double series is uniformly and absolutely convergent for all x and y in the rectangle except at (x_1, y_1) [HANTUSH, 1949]. So, after interchanging summations and rearranging terms, the drawdown distributions in the rectangle may be written as

$$\begin{aligned} s/(Q/2\pi T) = 2\sum_{n=1}^{\infty} R_n \Big\{ & \exp[-(\pi/2a)|y - y_1|\delta] - \exp[-(\pi/2a)|y + y_1 - 2b|\delta] \\ & + \sum_{m=1}^{\infty} \exp[-(\pi/2a)|4mb - (y - y_1)|\delta] - \sum_{m=1}^{\infty} \exp[-(\pi/2a)|4mb - (y + y_1 - 2b)|\delta] \\ & + \sum_{m=1}^{\infty} \exp[-(\pi/2a)|4mb + (y - y_1)|\delta] - \sum_{m=1}^{\infty} \exp[-(\pi/2a)|4mb + (y + y_1 - 2b)|\delta] \Big\} \quad \ldots (36) \end{aligned}$$

where $\delta = \sqrt{n^2 + (2a/\pi B)^2}$ and $R_n = (1/\delta) \sin (n\pi/2a)(x - a) \sin (n\pi/2a)(x_1 - a)$.

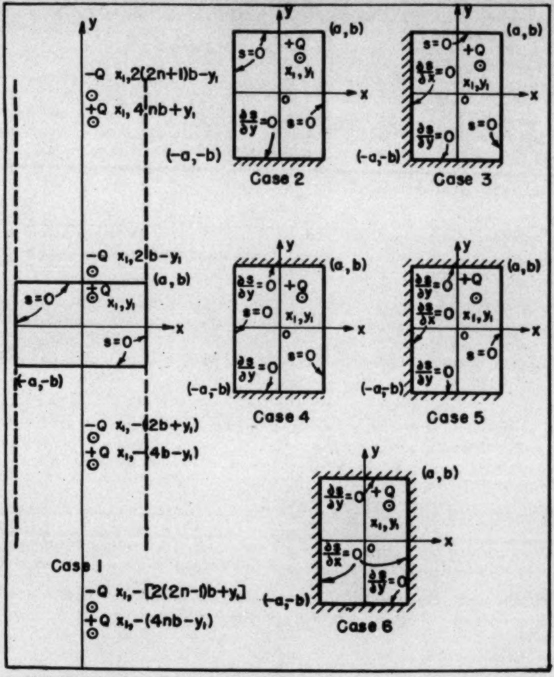
y
−Q x₁,2(2n+1)b−y₁
+Q x₁,4nb+y₁
−Q x₁,2b−y₁
+Q x₁,y₁
s=0
(a,b)
x
(−a,−b)
−Q x₁,−(2b+y₁)
+Q x₁,−(4b−y₁)
Case 1
−Q x₁,−[2(2n−1)b+y₁]
+Q x₁,−(4nb−y₁)
Case 2
∂s/∂y=0
o
Case 3
∂s/∂x=0
Case 4
Case 5
Case 6

Fig. 15--Diagramatic representation for the six cases of the rectangle

Since within the rectangle, $|y|$ and $|y_1| \le b$, then the values of $[4mb-(y-y_1)]$, $[4mb+(y-y_1)]$, $[4mb-(y+y_1-2b)]$, and $[4mb+(y+y_1-2b)]$ are always positive. Therefore, the absolute value sign may be dropped. After replacing the exponential functions by the appropriate combination of the hyperbolic functions, the sum with respect to m may be written as

$$\sum_m = -4 \sinh(\pi/2a)(y-b)\delta \sinh(\pi/2a)(y_1-b)\delta \sum_{m=1}^{\infty} [\exp(-2\pi b\delta/a)]^m \quad \ldots\ldots\ldots (37)$$

Since $Z/(1-Z) = \sum_{m=1}^{\infty} Z^m$ provided $|Z| < 1$, then if one puts $Z = \exp(-2\pi b\delta/a)$ one obtains

$$\sum_{m=1}^{\infty} [\exp(-2\pi b\delta/a)]^m = 1/[\exp(2\pi b\delta/a) - 1] \quad \ldots\ldots\ldots\ldots\ldots (38)$$

By virtue of (37) and (38) the solution (36) reduces to

$$s/(Q/2\pi T) = G'(x,y;x_1,y_1) = 2\sum_{n=1}^{\infty} R_n \left\{\exp[-(\pi/2a)|y-y_1|\delta] - \exp[-(\pi/2a)|y+y_1-2b|\delta]\right\}$$

$$-8\sum_{n=1}^{\infty} R_n \frac{\sinh(\pi/2a)(y-b)\delta \sinh(\pi/2a)(y_1-b)\delta}{\exp(2\pi b\delta/a) - 1} \quad \ldots\ldots\ldots\ldots\ldots\ldots (39)$$

The above procedure could be applied to the respective solutions for the cases of the infinite strip to obtain the solutions for the remaining cases of the rectangle. Instead, however, the solution of Case 1 will be used here to build up solutions for Cases 2-6.

Case 2: $s(\pm a, y) = 0$, $s(x, b) = 0$, and $(\partial/\partial y)\, s(x, -b) = 0$, Figure 15--In Case 1 let there be another well at the point $(x_1, -y_1)$. The drawdown due to these two wells is equivalent to that due to a single well at (x_1, y_1) in a rectangle of height b with a vanishing flux across the x-axis. To shift the origin of the coordinate axis to the center of the rectangle, y and y_1 should be replaced by $y + b/2$ and $y_1 + b/2$ respectively. And to make the height of the rectangle equal to 2b, replace b wherever it appears in the equation by 2b. Making these two transformations, the resulting equation will be the required solution.

Case 3: $s(a, y) = 0$, $s(x, b) = 0$, $(\partial/\partial x)\, s(-a, y) = 0$, and $(\partial/\partial y)\, s(x, -b) = 0$, Figure 15--The solution for this case is the sum of two solutions of Case 2 above due to two wells, one at (x_1, y_1) and the other at $(-x_1, y_1)$, if the following transformations are effected: (a) replace x and x_1 by $x + a/2$ and $x_1 + a/2$ respectively, and (b) replace a by 2a.

Case 4: $s(\pm a, y) = 0$ and $(\partial/\partial y)\, s(x, \pm b) = 0$, Figure 15--If two wells, one at (x_1, y_1) and the other at $(x_1, -y_1)$ exist in the region of Case 2, the flux across the x-axis vanishes. The replacement, in the resulting equation of y and y_1 by $y - b/2$ and $y_1 - b/2$ respectively, will translate the origin to the center of the rectangle. And the replacement of b by 2b will make the height of the rectangle equal to 2b. Thus the required solution for this case is obtained.

Case 5: $s(a, y) = 0$, $(\partial/\partial y)\, s(x, \pm b) = 0$, and $(\partial/\partial x)\, s(-a, y) = 0$, Figure 15--The drawdown distribution due to two wells located in the region of Case 4, one at (x_1, y_1) and the other at $(-x_1, y_1)$, will cause the flux across the y-axis to vanish. Hence, the solution to this case will be obtained by the replacement of a by 2a, and then the replacement of x and x_1 by $x + a$ and $x_1 + a$ respectively in the resulting equation.

Case 6: $(\partial/\partial x)\, s(\pm a, y) = 0$ and $(\partial/\partial y)\, s(x, \pm b) = 0$, Figure 15--In the region of Case 5, let a well be at (x_1, y_1) and let another one be at $(-x_1, y_1)$, then the drawdown due to these two wells will result in a vanishing flux across the y-axis. This drawdown is equivalent to that due to a single well situated at $(-x_1, y_1)$ in a rectangle whose sides are $y = \pm b$, $x = -a$, and $x = 0$.

In the equation which gives the drawdown of both wells the replacement of x and x_1 by $x - a/2$ and $x_1 - a/2$ respectively will make the center of the rectangle coincide with the origin of the x-axes. And again the replacement of a by 2a will make the width of the rectangle equal to 2a. Thus the present case is also solved.

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A SIMPLE FIELD INSTALLATION FOR MEASURING MAXIMUM EVAPOTRANSPIRATION

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(Contribution from the Department of Agronomy, North Carolina Agricultural Experiment Station, and the Tennessee Valley Authority, Division of Agricultural Relations and Hydraulic Data Branch, Knoxville, Tennessee; published with approval of the Director of Research, North Carolina Agricultural Experiment Station, as Paper No. 499 of the Journal Series.)

Abstract--Soil-filled gasoline drums (55 gal) have been used to measure maximum evapotranspiration at Waynesville, North Carolina. Installation involves no mechanical devices, and maintenance is at a minimum. Water is added manually to prevent water supply to the plants from becoming a limiting factor. Tensiometers are used to indicate when water must be added. Tanks are placed in the center of areas of the same vegetation. Data for one year under grass cover are presented and compared with values calculated from Thornthwaite's and Penman's formulas. The latter appears, upon statistical analysis, to fit the data better than the former.

Introduction--Recently, some workable formulas have been given with which the maximum evapotranspiration from a vegetative cover may be estimated [PENMAN, 1948; THORNTHWAITE, 1948]. Nevertheless, if only for the purpose of verifying such formulas, it still is very desirable to measure maximum evapotranspiration directly, particularly over fairly short periods of time, such as four or five days. It should be emphasized that this constitutes a different problem from that of measuring actual evapotranspiration when the soil is allowed to dry naturally between rains. Maximum evapotranspiration is defined as the total moisture return to the atmosphere from a surface completely covered with actively transpiring vegetation when soil-moisture tension is not limiting the rate of entry of water into the root system of the plant.

The conditions to be met by a good evapotranspirometer have been amply discussed by MATHER [1950]. Two very important factors, as pointed out by this author, are keeping the area surrounding the meter in the same crop which is grown in the meter, and irrigating an adequate area around it in a manner which will insure an even stand and a uniform microclimate around the evapotranspirometer.

A design for an evapotranspirometer in which a constant water table was maintained was given by Thornthwaite [WILM and Others, 1946] and the same design was later presented in greater detail by MATHER [1950]. A simpler form, in which water was applied from above was described by MATHER [1951]. For a more complete discussion of previous work, the reader is referred to the references cited.

Construction--The design for an evapotranspirometer given here originated from the desire to have the simplest possible construction, involving minimum cost of installation and maintenance. It may be considered a simplification of the design given by MATHER [1951], inasmuch as a separate pit for measuring overflow is eliminated. Construction details are shown in Figure 1. The tank is made of a 55-gal steel drum, painted inside and out with asphalt paint. A coarse copper screen is supported nine inches above the tank bottom, leaving a space for collection of the percolate. The rim of the drum protrudes two inches above the ground level.

In filling the drum with soil, an attempt was made to simulate natural profile conditions. While this might be of some importance in measuring actual evapotranspiration at a later date, it is not considered necessary for measurement of the maximum. Any soil with a reasonable water conductivity could be used since it is irrigated frequently. A steel pipe of one-inch diameter extends to the bottom of the tank, providing an opening through which the water level can be measured with a dipstick. The accuracy of measurement is 0.05 inch. A more accurate instrument could be used but it would not have the desired simplicity.

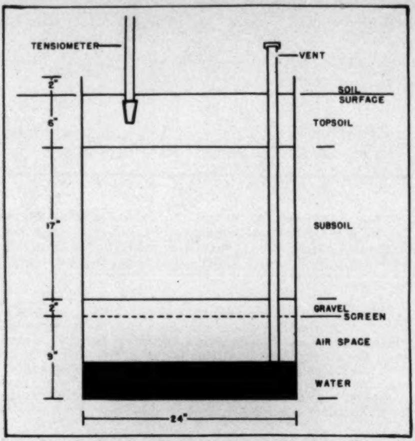

Fig. 1--Design of simple evapotranspirometer

Operation--The measurements consist of daily readings of the water level in the bottom of the tank. Water is sprinkled on the surface in a quantity sufficient to cause percolation through the whole soil mass on days when a tensiometer placed at two-inch depth indicates a moisture tension greater than 100 cm of water. It is generally considered that such a low tension is well below the level at which the transpiration rate is reduced. During the year of record it was necessary to irrigate 35 times, a total addition of 41.00 inches of water, supplementing 36.10 inches of rainfall during this period. When the water rises too high in the bottom, it is pumped out with a simple hand pump and the amount which is disposed of in this manner is measured. If the use of tensiometers is not possible or desirable, one may add an amount of water in excess of probable evapotranspiration on each day [see MATHER, 1951]. A standard rain gage at the site is read daily.

A triplicate installation was made. A native bluegrass-white clover sod containing a high proportion of weeds was maintained in the tanks and clipped periodically to keep the height between two and three inches. An area ten feet in diameter surrounding each tank was treated similarly and irrigated whenever the tanks were irrigated.

The computation of evapotranspiration loss is carried out as follows. For a given period of time, add the rainfall to the amount of water added by irrigation. Subtract from this total the amount of water that percolated through the soil block. The latter is the sum of the change in the water level in the bottom of the tank and the water pumped out, if any. The difference between total addition and total percolate is the loss by evapotranspiration if the moisture content of the soil block is the same at the beginning and at the end of the period. This condition can be met by choosing the period to lie between two time points which are a fixed time interval later than an irrigation or a soaking rain. The time interval is chosen so as to approximate the condition of field capacity throughout the barrel, for example, 24 or 48 hours. This is evidenced by the absence of measurable increase in the level of the water in the tank bottom in succeeding measurements.

Even so, the moisture content of the soil block may not be exactly the same at the beginning and end of the period of measurement. By taking the time points sufficiently far apart, the effect of this error is diminished. Furthermore, combining two or more periods into a larger one cancels the error mentioned, since the ending point of one period is the starting point of the next one.

Another method of evaluating soil-moisture conditions would be to have moisture recording devices at several depths in the barrel. Since low tensions are maintained, one might employ tensiometers. However, one could not have too many of these in a small area such as was used and, moreover, use of any type of existing moisture meter would render the method far less simple.

Table 1--Maximum evapotranspiration at Waynesville, North Carolina, 1952-1953

Period of measurement noon to noon	Average daily temperature	Average daily loss by periods				Thornthwaite's average calculated value
		Tank			Average	
		1	2	3		
1952 1952	°F	in	in	in	in	in
Aug. 17 - Sep. 10	66.1	0.127	0.110	0.115	0.117	0.125
Sep. 10 - Oct. 1	63.6	0.085	0.085	0.090	0.087	0.105
Oct. 1 - Oct. 11	54.5	0.094	0.064	0.074	0.077	0.064
Oct. 11 - Oct. 19	56.4	0.088	0.075	0.100	0.088	0.069
Oct. 19 - Oct. 26	45.0	0.057	0.075	0.043	0.058	0.030
Oct. 26 - Nov. 2	44.6	0.100	0.085	0.071	0.085	0.029
Nov. 2 - Nov. 21	46.4	0.037	0.032	0.047	0.039	0.034
Nov. 21 - Dec. 11	41.3	0.016	0.021	0.001	0.013	0.020
1953						
Dec. 11 - Jan. 3	36.4	0.002	0.006	0.006	0.005	0.008
1953						
Jan. 3 - Jan. 12	40.1	0.002	0.001	....[a]	0.001	0.019
Jan. 12 - Jan. 25	43.8	0.025	0.025	0.009	0.020	0.026
Jan. 25 - Feb. 19	40.1	0.037	....[a]	....[a]	0.037	0.016
Feb. 19 - Feb. 23	44.1	0.037	....[a]	....[a]	0.037	0.049
Feb. 23 - Mar. 6	46.7	0.046	0.037	0.028	0.037	0.036
Mar. 6 - Mar. 27	49.3	0.044	0.038	0.044	0.042	0.046
Mar. 27 - Apr. 4	51.6	0.100	0.089	0.080	0.090	0.058
Apr. 4 - Apr. 14	54.1	0.108	0.118	0.118	0.115	0.069
Apr. 14 - Apr. 22	44.8	0.111	0.099	0.099	0.103	0.035
Apr. 22 - Apr. 27	59.8	0.124	0.064	0.124	0.104	0.096
Apr. 27 - May 3	61.9	0.196	0.196	0.180	0.191	0.108
May 3 - May 13	61.0	0.100	0.100	0.080	0.093	0.105
May 13 - May 17	67.8	0.160	0.160	0.160	0.160	0.140
May 17 - May 23	68.6	0.166	0.183	0.150	0.166	0.145
May 23 - May 27	72.1	0.150	0.125	0.150	0.142	0.164
May 27 - May 29	64.3	0.150	0.150	0.200	0.167	0.123
May 29 - May 31	72.8	0.300	0.250	0.250	0.267	0.167
May 31 - June 3	66.0	0.233	0.200	0.233	0.222	0.135
June 3 - June 5	64.8	0.250	0.250	0.200	0.233	0.128
June 5 - June 9	74.5	0.215	0.240	0.240	0.232	0.182
June 9 - June 18	71.4	0.172	0.132	0.172	0.159	0.165
June 18 - June 21	74.2	0.133	0.133	0.167	0.144	0.178
June 21 - June 26	71.0	0.196	0.216	0.176	0.196	0.161
June 26 - July 1	73.8	0.146	0.122	0.166	0.145	0.177
July 1 - July 4	73.5	0.160	0.160	0.160	0.160	0.173
July 4 - July 12	69.5	0.161	0.161	0.161	0.161	0.153
July 12 - July 17	67.4	0.143	0.143	0.143	0.143	0.140
July 17 - July 26	71.7	0.124	0.124	0.124	0.124	0.164
July 26 - July 29	71.0	0.165	0.200	0.200	0.188	0.159
July 29 - Aug. 1	76.8	0.133	0.100	0.133	0.122	0.154
Aug. 1 - Aug. 4	74.7	0.184	0.217	0.150	0.184	0.170
Aug. 4 - Aug. 9	73.4	0.132	0.132	0.152	0.139	0.163
Aug. 9 - Aug. 12	66.8	0.167	0.200	0.167	0.178	0.129
Aug. 12 - Aug. 15	70.7	0.150	0.150	0.175	0.158	0.149
Aug. 15 - Aug. 27	67.5	0.093	0.102	0.093	0.096	0.134
Aug. 27 - Aug. 31	69.0	0.150	0.175	0.175	0.167	0.141
Annual totals		32.76	31.53	31.77	31.99	29.10

[a] Surface runoff entered tanks - amount unknown.

Results and discussion--Results for a period of one year are given in Table 1. The measured values were compared with values computed from THORNTHWAITE's [1948] formula, in which the daily average value for the air temperature at Waynesville, North Carolina, was used. The calculated daily evapotranspiration rates were then averaged over the period in question and are shown in the last column in Table 1. The data in Table 1 were examined by a computation of the regression of measured values on the computed ones, and by making an analysis of variance. The latter showed that the variance in the data owing to disagreement between tanks within periods was far less than the deviations of the period means from regression. In other words, the computed values are taken from a model that does not adequately represent the phenomenon. The regression equation is $Y = 0.968X - 0.018$, in which Y are estimated values and X the computed ones. The standard error of the regression coefficient was 0.097.

Table 2--Average daily evapotranspiration by months at Waynesville, North Carolina, 1952-1953

Month	Measured	Thornthwaite		Penman	Temperature	
		Daily[a]	Monthly[b]		1952-1953	Seven-year average
1952	in	in	in	in	°F	°F
September	0.096	0.105	0.110	0.097	63.7	64.5
October	0.077	0.050	0.068	0.060	51.2	56.3
November	0.034	0.028	0.027	0.039	44.5	45.1
December	0.006	0.013	0.011	0.021	38.7	39.0
1953						
January	0.028	0.021	0.018	0.030	41.7	41.5
February	0.037	0.023	0.019	0.052	41.3	41.5
March	0.047	0.044	0.038	0.081	48.6	47.3
April	0.114	0.067	0.072	0.125	53.2	54.6
May	0.147	0.132	0.103	0.150	66.2	60.4
June	0.181	0.164	0.143	0.166	71.3	67.4
July	0.148	0.159	0.161	0.151	71.0	70.8
August	0.134	0.145	0.146	0.131	69.9	70.1
Annual total	31.99	29.10	27.95	33.61		

[a] 'Daily' indicates that daily air temperatures were used in calculation.
[b] 'Monthly' indicates that seven-year mean monthly temperatures were used.

In Table 2 results of different methods of estimating evapotranspiration are compared. The first column of numerical data gives the average daily measured rate over monthly periods. The second column gives the average values computed with THORNTHWAITE's [1948] formula using actual daily air temperatures, while the third column gives results of the same formula employing the seven-year average monthly air temperatures. Column four gives values calculated with PENMAN's [1948] formula, using monthly temperatures for the year of measurement. In using PENMAN's [1948] formula, the values for an open water surface were multiplied by 0.7 for all months. Air temperature, dewpoint, wind velocity, and sky cover for the period of measurement were taken from official records for Asheville, North Carolina, the wind velocity values being adjusted to two-meter height.

The data of Table 2 were analyzed in the same manner as the data of Table 1. Table 3 shows that all three methods of calculation fail to be true models of the experiment data. The calculation with the Penman formula, however, agrees much better than the other two. This conclusion is supported by the magnitude of the three correlation coefficients, shown in Table 3, which also gives the coefficients of determination, the regression equations, and the standard errors of the regression coefficient.

It should be stated that, with all three regression coefficients being insignificantly different from unity, all three methods give, as a whole, a reasonable agreement with the data. The superiority of Penman's method in this situation is, however, unmistakably clear.

The adequacy of a triplicate installation for the problem that was investigated appears from the result that the standard error in the daily evaporation rate, averaged over the three tanks for one period, was 0.007 inch/day. For similar purposes, duplicate installations would probably be adequate on the basis of the foregoing.

Table 3--Characteristics of the regression of observed evapotranspiration rates, averaged by months, on values computed by three different methods

Method	Ratio of mean square due to deviation from regression to mean square experimental error[a]	Correlation coefficient	Coefficient of determination[b]	Regression equation	Standard error of regression coefficient
Thornthwaite (monthly)	72.5	0.931	0.867	$Y = 0.972X + 0.013$	0.120
Thornthwaite (daily)	48.1	0.953	0.908	$Y = 0.943X + 0.013$	0.093
Penman	28.0	0.974	0.949	$Y = 1.081X - 0.012$	0.072

[a] Minimum value is 3.3 at one per cent probability level.

[b] Showing the fractional extent to which the data can be explained on the basis of the particular method of computation.

Table 4--Total monthly evapotranspiration at Waynesville, North Carolina, 1952-1953

Month	Measured	Thornthwaite		Penman	Rainfall 50-year mean
		Daily	Monthly		
1952					
September	2.88	3.15	3.29	2.91	3.00
October	2.39	1.56	2.10	1.86	3.04
November	1.02	0.83	0.81	1.17	2.25
December	0.19	0.40	0.33	0.65	4.61
1953					
January	0.86	0.65	0.55	0.93	3.75
February	1.04	0.63	0.54	1.46	4.04
March	1.45	1.38	1.18	2.51	5.05
April	3.43	2.02	2.15	3.75	3.68
May	4.56	4.11	3.20	4.65	3.98
June	5.42	4.92	4.29	4.98	4.12
July	4.59	4.94	4.99	4.68	4.60
August	4.16	4.51	4.52	4.06	4.21
Annual total	31.99	29.10	27.95	33.61	46.33

Table 4 presents the total monthly evapotranspiration as found and computed by the various methods and compares it with the 50-year mean monthly rainfall. The data in Table 4 are graphically represented in Figure 2, which shows the nature of the disagreement between computed and observed values. In particular, it appears that the computed values following Thornthwaite (daily temperatures) show a lag of about a whole month in the spring and early summer, with respect to the Penman curve and the observed values, causing serious under-estimates in that period of the year. VAN WIJK and Others [1953] have shown that this lag should exist and that its value would be equal to the lag of air temperature behind radiation, which is about one month (compare with temperature data in the last column of Table 2). The data presented in Figure 2 substantiate the ideas of the aforementioned authors.

There exists some question as to the comparability between evapotranspirometers that are operated with a fixed water table and those to which water in excess is added. With the latter, if water is added daily, there can be no doubt that the soil moisture is always maximally available. In the former case the proposition is not so certain. Obviously, one cannot maintain too high a water table and still expect normal plant growth. But if the water table is at a depth of 35 cm or more [MATHER, 1950], it is possible that the upward flow of water through the soil cannot keep pace with the rate of removal by the roots, especially in the area immediately surrounding the

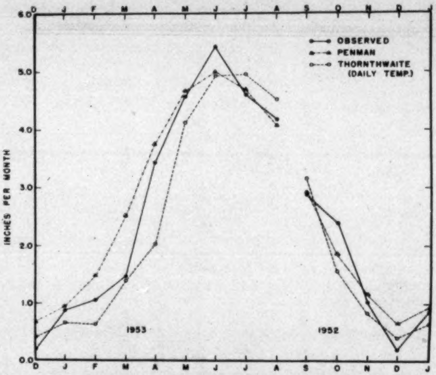

Fig. 2--Comparison of observed and calculated monthly evapotranspiration rates (Waynesville, North Carolina)

roots. Probably, the inequalities in moisture tension are obliterated during the night period. During the day, however, moisture tension may well limit evapotranspiration in spite of a water table located permanently at 35-cm depth. The cause is the sharply reduced conductivity of soil for water at negative pressures.

Clearly, an advantage would thus be established in favor of using evapotranspirometers that are watered from above because one could be more certain that soil-moisture tension would not prevent transpiration from occurring at the maximum rate. In addition, their operation is quite simple as compared to the other type.

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SALINATION OF SOIL BY SALTS IN THE IRRIGATION WATER

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Abstract--This paper is a partial report on the quality of irrigation water. It is principally concerned with the salts of irrigation water which form salines in the soil. A method has been suggested for calculating the potential salinity of water and listed as 'effective salinity.' New conversion factors have been listed for changing from milliequivalents to parts per million or pounds of salt per acre foot for the soluble salts of effective salinity. A new standard has been suggested for the total salts of irrigation water based on the effective salinity, followed by a discussion concerning the application of this standard to irrigated agriculture.

Introduction--For some years investigators interested in irrigated agriculture have been concerned with the quality of water used in irrigation and from time to time have set up tentative standards as a guide to its quality. One of the standards more recently established and widely distributed in California is given in Table 1. If a water with one constituent listed in Table 1 falls in a poorer class, it automatically is placed there, although it is probably not as poor as one having two constituents in this class.

Because of diverse climatological conditions, crops, and soils, it has not been practical to establish rigid limits for all conditions involved. Instead, field experience has indicated that this classification should be for the purpose of orientation and as a guide, and that local conditions must be considered in judging the suitability of a water for irrigation. The classification listed in Table 1 is the result of the research and experience of various investigators.

History--So far as the author knows, the first standards were reported by mimeograph leaflet in a cooperative agreement between Agricultural Extension Service of the University of California and the United States Department of Agriculture in 1931. This standard set the electrical conductance limits for the different classes of water the same as in Table 1, the boron a little higher, the sodium for Class 2 water at 40 pct and Class 3 at 70 pct, chlorides and sulfates at four and ten milligram equivalents (me) for the lower levels of Classes 2 and 3 waters. In 1936 these standards were reissued in mimeograph form, the principal change being to reduce the chloride content to two and four me for the lower limits of Classes 2 and 3 waters respectively, and to establish different classes for plants sensitive or tolerant to boron. In 1943 the standards in Table 1 were issued and with the frequent remimeographing have received wide distribution in California.

Table 1--Qualitative classification of irrigation waters[a]

Item	Class 1	Class 2	Class 3
	Excellent to good	Good to injurious	Injurious to unsatisfactory
$K \times 10^5$ at 25°C[b]	Less than 100	100 -300	More than 300
Boron, ppm	Less than 0.5	0.5- 2.0	More than 2.0
Sodium, pct[c]	Less than 60	60 - 75	More than 75
Chloride, me/ℓ	Less than 5	5 - 10	More than 10

[a] From Interpretation of Analyses of Irrigation Waters and the Relative Tolerance of Crop Plants by L. V. Wilcox and O. C. Magistad, mimeographed by the U. S. Regional Salinity Laboratory, 1943.

[b] Specific electrical conductance $K \times 10^5$ at 25°C is reported in reciprocal ohms/cm, multiplied by 10^5, and provides an index of total dissolved electrolytes or total salinity. Dividing the conductance by ten gives an approximation of the salt content in me/ℓ. Multiplying the conductance by seven gives a rough estimate in parts per million (ppm) of total salts.

[c] Sodium percentage is computed by the formula $(Na \times 100)/(Na + Ca + Mg)$, when these bases are expressed as me/ℓ.

Classifications for irrigation water other than those mentioned above have been suggested. EATON [1935] suggested five classes in which the conductance covered approximately the same range as Table 1. The per cent/sodium for each class was divided at intervals of 20 pct. Boron started at an upper limit for Class 1 at 0.25 ppm and for Class 5 above 3.0 ppm. The other classes fell in between these limits. The other mineral constituents of waters were not listed. SCOFIELD [1935] enlarged on Eaton's classification by dividing the boron into three groups according to plant tolerance and keeping the five general classes of water, thus giving 15 classifications for boron. Chlorides and sulfates were added with a concentration of four me as the upper limit for Class 1 water and above 20 me for each in Class 5.

EATON [1941] and others listed a classification for irrigation water with sodium starting at 40 pct for Class 2 and 70 pct for Class 3 waters. Plants were divided in two groups, either sensitive or tolerant to boron. The lower limit for chlorides in Class 2 water was two me, for Class 3 water six me, and for sulfates Classes 2 and 3 began at four and 12 me, respectively. Total concentration was not included. MAGISTAD and CHRISTIANSEN [1944] listed standards the same as those in Table 1 with the exception that chlorides were omitted. WILCOX [1948] published standards having five classes with the same range for electrical conductivity, per cent/sodium, and boron concentration as those reported by Scofield in 1936 but excluding chloride and sulfate. This classification of irrigation waters has been accepted by some Federal agencies and states and given fairly wide publicity. Wilcox suggested the electrical conductivity be reported as $EC \times 10^6$ at 25° C or as micromhos/cm instead of conductance as $K \times 10^5$. This is also receiving general acceptance.

Source of salines--The classifications for irrigation water described above have relied on electrical conductance as the criterion for total salt concentrations. The range is from 100,$K \times 10^5$ at 25° C (1000 millimhos), or below for the best quality to 300 or above for the poorest quality water. This range has been divided into three or five classes. In the author's experience, the electrical conductance measurement of an irrigation water is not a good valuation for the potential accumulation of salines in a soil.

When nonsaline soils, irrigated for some years, gradually develop a high salt concentration, it is usually due to the accumulation of soluble salts brought in with the irrigation water. Under high water-table conditions, the concentration of salts occasionally may be due to soluble salts from the deep subsoils coming to or near the soil surface with the rise of the water table, and some salts may be dissolved from the soil by the water table. This dissolving of the soil minerals is probably a minor source in salt accumulation for a short period of time, and most of the salt increase may be directly attributed to the irrigation water. In the absence of a high water table, the irrigation water would be the main source of salts in the development of a saline soil.

A number of workers show the soil solution in well-drained soil to be more concentrated than the irrigation water used. Under this condition SCOFIELD [1935] estimates that the soil solution in heavily leached soil may be twice as concentrated as the irrigation water; and under less severe leaching where the water is used sparingly, the difference is much greater, often eight times or more the concentration of the irrigation water. This concentration of salts in the soil is due to two factors, evaporation from the soil surface and water used by the plants in transpiration. Plants usually remove only a small percentage of the total salt occurring in the irrigation water.

Investigators of alkali reclamation and related fields recognize the limited solubility of calcium and magnesium carbonates and calcium sulfate. This report is concerned with these slightly soluble salts which may occur in the irrigation water and how their presence affects the accumulation of soil salines. These salts of limited solubility do not contribute to the formation of saline soils.

Effective salinity of irrigation water--In this discussion, assume the following conditions prevail. The irrigated soil is in a low rainfall area, and no extensive leaching of the soil occurs from application of more water than will be lost by surface evaporation or vegetative transpiration. These conditions are usually found in soils with a hardpan or claypan high water table; a highly stratified, heavy clay; or in permeable soils where the water is used sparingly. The salts from the irrigation water will accumulate in the soil. As the soil solution becomes concentrated, certain salts will precipitate. Because of the low solubility, the first to precipitate will be calcium carbonate followed by magnesium carbonate and finally by calcium sulfate. Other salts normally occurring in irrigation water in any significant concentrations are extremely soluble and accumulate in the soil solution as salines. EATON [1950] discusses the calcium and magnesium carbonate precipitations as they affect the sodium percentage in the soil solution. However, JOSEPH [1925], working with the irrigation waters of the Blue Nile, points out that calcium carbonate, because of precipitation by evaporation, should not be included as 'permanently soluble material' in the formation of alkali soils.

The solubility of calcium sulfate, about 28 me or 2410 ppm in pure water, is high when compared to calcium and magnesium carbonates but not sufficiently concentrated under our present standards to produce a saline soil. Many of our salt-sensitive plants grow satisfactorily in gypsiferous soils. To be sure, gypsum (calcium sulfate) in the irrigation water or in the soil will contribute somewhat to the salinity of a soil, adding to the more soluble salts in the soil solution. Other soluble salts in the soil solution will influence the solubility of gypsum, and also calcium and magnesium carbonate. Salt concentrations in the saline range for soil may increase the solubility of gypsum by several milliequivalents, and extremely high concentrations may increase the solubility by 50 pct or more. When the sulfate or calcium ion predominates in the saline soil solution, the common ion will suppress the solubility of gypsum, under certain conditions to a third or more, based on the solubility in pure water. These same general principles hold for the solubility of calcium and magnesium carbonates except pH is an important factor in their solubility. Calcium sulfate alone or in combination with other salts will not in itself bring about a saline soil.

Calcium and magnesium carbonates and calcium sulfate should not be considered in establishing standards for total salinity as is now the practice in the use of electrical conductance. The remaining soluble salts forming salinity are listed as 'effective salinity' of an irrigation water in Table 2. For example, Water 1 has a conductance of 103 with a total of 12.2 me. Upon concentration of this water in the soil solution, the calcium precipitates as the carbonate, followed by the precipitation of magnesium carbonate. As there is more bicarbonate than calcium and magnesium, these two cations do not contribute to salinity and are subtracted from the total cations, leaving 3.6 milliequivalents of soluble salts, or 'effective salinity.' Thus the salinity potential of the water is reduced from 12.2 me salt to 3.6. This water has been used many years on well-drained soil without serious problems of salt accumulation.

Table 2--Analyses of selected well and river waters used for irrigation

Number[a]	$K \times 10^5$ at 25°C	Na	Cations				Anions			Effective salinity	
			Ca	Mg	Na	Total	HCO_3	SO_4	Cl		
		pct	me	me	me	me	me	me	me	me	Na pct
					Well waters						
1	103	29	2.6[b]	6.0[b]	3.6	12.2	9.6[c]	1.5	1.1	3.6	100
2	187	23	11.1[b]	7.0	5.3	23.4	2.7[b]	19.9[c]	0.5	12.3	43
3	330	26	28.5[c]	3.1	11.3	42.9	1.1[b]	25.4[b]	15.0	16.4	69
4	302	90	1.8[b]	1.1[b]	26.5	29.4	3.0[c]	14.7	11.9	26.5	100
5	75	90	0.6[b]	0.1[b]	6.3	7.0	1.9[c]	1.6	3.8	6.3	100
6	69	24	3.9[b]	1.5[c]	1.7	7.1	4.8[b]	0.3	1.9	2.3	74
7	48	91	0.3[b]	0.1[b]	4.2	4.6	1.8[c]	2.7	0.1	4.2	100
8	38	31	1.9[b]	0.9[c]	1.3	4.1	2.6[b]	0.8	0.4	1.5	87
9	32	18	1.9[b]	1.2[c]	0.7	3.8	3.0[b]	0.0	0.5	0.8	88
					River waters						
1	61	50	1.8[b]	1.2[b]	3.0	6.0	3.0[b]	2.7	0.3	3.0	100
2	74	41	2.5[b]	1.8	3.0	7.3	2.2[b]	1.7[c]	3.4	4.8	63
3	117	39	5.1[b]	2.3	4.7	12.1	2.5[b]	7.2[c]	2.3	7.0	66
4	51	32	1.3[b]	2.4[b]	1.8	5.5	3.8[c]	0.6	1.0	1.8	100

[a] Well water no. 1--University farm well no. 10, Yolo County; no. 2--Cuyama valley, Santa Barbara County; no. 3, 5, 7, 8--Kern County; no. 4--Fresno County; and no. 6, 9--San Joaquin County. River water no. 1--Susan; no. 2--San Joaquin; no. 3--Colorado; and no. 4--Cache Creek.

[b] These ions will precipitate as the soil solution is concentrated.

[c] These ions will only partially precipitate as the soil solution is concentrated.

Water 2 is a high sulfate water with a total cation content of 23.4 me. The first precipitation in this water is the bicarbonate as calcium carbonate. As there is an excess of calcium over bicarbonate, no magnesium precipitation is involved. The remaining calcium precipitates as the sulfate, and the salinity of the water is reduced by the calcium concentration to 12.3 me. After this water was used on a loam soil for seven years, the salinity increased to a concentration that reduced potato yields by 50 pct, and it was difficult to obtain uniform germination of seeds. Deep percolation of irrigation water was difficult due to clay lamination in the subsoil; consequently, much of the salt added remained in the surface three feet of soil.

Water 3 has a high salt content with a conductance of 330 and a total ionic concentration of 42.9 me. The reduction in concentration is by precipitation of calcium carbonate and sulfate. Due to the high calcium content, the reduction in salinity is determined by the bicarbonate and sulfate ions for a total of 26.5 me, leaving in solution 16.4 me effective salinity. This water was applied sparingly on a sandy loam soil and crop yields were reduced by the accumulation of salines.

The three waters discussed above show a marked reduction in potential soil salinity, 'effective salinity,' as compared to the present method of classifying according to conductance or total milliequivalent salt. Measurements involving conductance of the irrigation water are not the best method in estimating the salination of a soil. Even with the reduction in potential soil salinity of the above waters, two of them produced saline soils because of the relatively high effective salinity plus insufficient leaching of the soil.

Some waters precipitate few salts upon concentration in the soil solution, as Water 4. In this example the reduction in salinity is by the precipitation of 2.9 me calcium and magnesium carbonates from a total salinity of 29.4 me, giving 26.5 me effective salinity. With this water the conductance or total concentration is a fair measure of effective salinity.

The calculation of effective salinity is more applicable to waters of low salt content, that is, having a conductance of less than 100, than those of a higher salt concentration because these are frequently recognized as possibly harmful for some or all crops. Waters 5 and 6 with a conductance of 75 and 69, respectively, and approximately the same total salt concentration have widely different effective salinities. Water 5 has a high percentage of the total salts occurring as effective salinity (6.3 me), whereas Water 6 is reduced to approximately a third (2.3 me). Additional examples of varying effective salinity in low salt water of nearly the same total concentration are given in Waters 7, 8, and 9. The effective salinity ranges from 4.2 to 0.8 me. The above examples indicate that the potential salinity cannot be judged by conductance or total salt content, and the slightly soluble salts of calcium and magnesium carbonates and calcium sulfate should not be considered in classification of a water for accumulation of salines in the soil.

Four surface waters diverted from rivers or streams in California for irrigation purposes are listed in Table 2. These show a reduction from total salts, when calculated as effective salinity, of 34 pct in river water for Water 2 (San Joaquin) to 67 pct for Water 4, Cache Creek. With the exception of Water 4, the others give rise to soil salinity when deep percolation is impaired. Notable is the accumulation of salt in the Imperial Valley from Colorado River water, no. 3. This water has an effective salinity of 7.0 me, which is sufficiently high to account for all the accumulated salts of Imperial Valley.

Salination of a soil by irrigation water--For irrigation waters, an approximate relationship exists between conductance, parts per million, milliequivalents per liter, and tons of salt per acre foot. For example, a conductance of 100 ($K \times 10^5$ at 25° C) is approximately equivalent to 700 ppm, ten me total salt, or a ton of salt per acre foot. These are very useful relationships in expressing total salts of an irrigation water in various terms. However, in the precipitation of calcium and magnesium bicarbonates and calcium sulfate, most of the salts of high molecular weights are removed from solution, which changes the relationship that exists in the original irrigation water. A better relationship for effective salinity is one milliequivalent to equal about 55 ppm or 15 lb of salt per acre foot of water. Then ten me effective salinity is approximately 550 ppm or three-fourths ton of salt per acre foot of water. Assuming the salts of an irrigation water remain in the soil to the depth of plant rooting, then the degree of salination will be in proportion to the quantity of water used in evapotranspiration and the effective salinity of the irrigation water.

If 0.2 pct by weight of dry soil is used as a criterion for the limit between saline and nonsaline soil, then to bring an acre foot of soil to this concentration requires 7140 lb of salt. This calculation is based on a cubic foot of soil weighing 82 lb. (When four millimhos of the saturated extract is used as a standard for the lower limits of salinity, the total salt is about 6000 lb or 0.18 pct dry weight of soil for soils of intermediate water-holding capacity.)

As each milliequivalent effective salinity contributes about 150 lb of salt per acre-foot of water, it takes 48 me to bring each acre foot of soil to 0.2 pct of salt, or a water containing ten me effective salinity requires 4.8 ac ft to reach this salt percentage. If the rooting depth of the plant is six feet and salts are not leached from this rooting zone, then ten me of effective salinity requires 28.8 ac ft of water. Assuming this is applied at the rate of 2.5 ft per year, it will require approximately 11 years to salinize a soil uniformly to 0.2 pct salt. (This is an idealized situation, as field soils are rarely uniformly salinized.) The depth of soil or the depth of rooting of the plant species involved determines the number of years required to salinize a soil provided leaching is not involved.

Discussion--The above calculations assume no leaching of a soil below the root development of the plant. Under field conditions, this does not normally follow. Under most conditions of field irrigation, some movement of soil moisture below the root zone occurs. Irrigated high water-table soils usually have a natural or artificial drainage system. Although all the accumulated salts are not removed in the drainage water, a balance may be established so that accumulation of salines is held at a concentration sufficiently low to permit the growth of agricultural plants. The salts in some high water-table areas may not be due entirely to the effective salinity of the irrigation water but may have been in the original soil before irrigation was started or, as some authorities suggest, may have been brought up from salt previously deposited in the deep subsoil by the rise of the water table. Under these conditions, any effective salinity of irrigation water only aggravates the salt condition of the soil.

Many other conditions may seriously reduce deep percolation of irrigation water within a reasonable time, such as high sodium soils, stratified soils, clay lenses, high clay content in surface or subsoil, and dense or compact subsoils. These soil conditions may prevent sufficient leaching to remove the salines of the irrigation water. However, some leaching may be accomplished by holding the water on the surface for a long period of time. An extreme example is the removal of salines on very heavy soils by rice culture in which the soil is submerged for about five months. Most hardpans and some claypans are practically impermeable to water. Even these may have cracks or ruptures through which water and accumulated salts may drain. Under conditions of restricted drainage, different standards should be established for effective salinity of an irrigation water than in deep, open soils where leaching is easily accomplished. Table 3 suggests tentative standards for effective salinity of irrigation water with and without restricted drainage. The assumption is that one to two me of effective salinity will be removed in crop production. The crucial concentrations are those listed in Class 1 for the three soil conditions. Classes 2 and 3 indicate increasing concentration, and the build-up of soil salinity should be checked periodically and irrigation practices adjusted to remove salinity with the minimum loss of water. Class 1 water is not considered safe under some extreme conditions encountered in the field.

Table 3--Tentative classification for effective salinity of irrigation waters

Soil conditions	Terms used	Class 1	Class 2	Class 3
Little or no leaching of the soil can be expected	me	3	3- 5	5
	ppm	165	165- 275	275
	lb/ac ft	450	450- 750	750
Some leaching but restricted; deep percolation or drainage slow	me	5	5- 10	10
	ppm	275	275- 550	550
	lb/ac ft	750	750-1500	1500
Open soils; deep percolation of water easily accomplished	me	7	7- 15	15
	ppm	385	385- 825	825
	lb/ac ft	1050	1050-2250	2250

The circumstances, other than those listed in Table 3, under which an irrigation water is to be used should be taken into consideration. In areas of high annual rainfall where the soil is wet to six feet or more in depth, or below the depth of rooting of the crop grown, the concentration of effective salinity could be increased for all classes. In low rainfall areas some leaching may be desirable; but due to low farm irrigation efficiencies, ranging from 20 to 80 pct of the water delivered to the farm, most surface soils are adequately leached for removal of any excess salts. In fact, over-irrigating or low farm irrigation efficiencies result in damage to more soils, due to the rise of a water table with increased salinity, than irrigating sparingly and allowing the salts to accumulate. In pumped areas where the water table is low, the water is used sparingly, and is of high effective salinity, an occasional over-irrigation may be beneficial in removing salines. Only a few isolated cases are known to the author in which serious salinity problems have developed due to the use of irrigation water with a relatively high salt content in the absence of a high water table. Careful investigation should be made to determine whether sufficient deep percolation is taking place in the ordinary irrigation practice to remove the salt from the surface soil. Where surface water is used for irrigation and the potentiality of developing a high water table may exist, irrigations should be limited to evapotranspiration with the minimum of excess water to remove the salines.

Other factors under study for the classification of irrigation waters--The above discussion has been limited to the accumulation of total salines. This is only one of many factors to be considered in classification of irrigation water (Table 1). These factors are being studied separately and in relation to each other with the view of integrating them into an improved water classification system. Some of these, particularly per cent sodium, are probably more important than effective salinity. The sodium percentage of the effective salinity (Table 2) is being studied along with Eaton's suggestion of 'residual sodium carbonate' in the irrigation water on the base exchange of the soil. The per cent sodium of the base exchange complex and other conditions affecting the dispersal of the soil clays are extremely important in permeability studies and in many cases may be the controlling factor in salination of a soil. In some instances individual ion toxicity may be important, and this is being critically reviewed.

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DISCUSSION

Bruce F. Beacher (U. S. Bureau of Reclamation, Denver, Colo.)--Our review of the report discloses that it is a creditable contribution to the field in bringing into focus some of the fundamental physico-chemical reactions and solution equilibria which have not been sufficiently recognized and evaluated in water-quality standards.

The proposed classification of irrigation water is one which interrelates 'soil conditions' and 'effective salinity.' It attempts to account for ionic equilibria in soil solutions. General ionic relationships and hypothetical combinations of ions in water have been recognized in quality standards for some time [STABLER, 1911; FRENCH, 1939]. More recently emphasis has been placed on the interrelation of the ions and total concentration with the soil, crop, and drainage factors [THORNE and THORNE, 1951; WILCOX, 1948; U. S. SALINITY LABORATORY, 1954]. The attempt to account for ionic equilibria, one of the oldest and most important branches of study in physical chemistry, of irrigation water and soil solutions in general water standards is well intended, but of questionable validity and perhaps undesirable. Ionic interactions and the formation of complex salts such as $Na_2Ca(CO_3)_2$ [BUEHRER and WILLIAMS, 1936] are likely not only among the ions of the irrigation water as the concentration changes, but between these ions and the soluble and colloidal phases of the soil. The fact that bicarbonate exceeds calcium and magnesium in the irrigation water is no guarantee that the sodium ion will dominate the soil solution. We cannot maintain, with any degree of certainty, that one general type of reaction will occur under all conditions. The general principle of the proposed classification, therefore, may be entirely applicable to one area, but unsuitable for use in another.

But beyond the specific theoretical limitations involved, there are several features which apply generally to all classifications of this type: (1) a continuation of major emphasis on chemical character of the water, (2) a trend toward more complex standards, and (3) the inverse relation of quality and total salinity. Chemical data are essential for any prognosis of use suitability or restrictions, but an analysis represents a static condition. The possibility of developing generally applicable classes expressing the complex dynamic interrelationships of water, soils, drainage, crops, climate, and irrigation practice is remote. The author recognizes the various controlling factors in his discussion and indicates that they are being studied with a view to integrating them into an improved water classification. The result can only be more complex standards. It is important to emphasize the author's request that the classification should be for the purpose of orientation and that local conditions must be considered in judging the suitability of a water for irrigation. The fact is that local standards must be evolved if any classification procedure is followed. It would be preferable to de-emphasize general standards and to emphasize general procedures for correlating chemical data with the other factors affecting use suitability and restrictions. More attention must be directed to management and use of the water rather than to its chemical nature and declarations of its existing quality. With respect to the well-established procedure of inversely relating suitability to salinity, it has been observed that moderately salinized water may be more desirable for use under certain soil and drainage conditions than the relatively pure supplies. We should continue to recognize such exceptions when they occur. KELLEY [1940] said, "At best the irrigation engineer can set up only tentative limits, and at present these must be based mostly on practical experience in the localities in question." It appears that the tentative aspect of water classifications will continue to be the only certain feature of them.

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W. W. Hastings (U. S. Geological Survey, Washington, D. C.)--The Geological Survey makes systematic surveys to provide basic data on the chemical characteristics of natural waters with reference to their suitability for industrial, municipal, agricultural, and other uses. Such investigations involve not only systematic collection, but also the compilation and evaluation of basic data relating to the chemical quality of surface and ground waters. Therefore, water-quality criteria in evaluating the usefulness of the waters are of particular interest to the Geological Survey. The factual reports issued by the Geological Survey usually bring into account available standards of water quality so as to provide the reader with available facts to assist him in determining the suitability of the waters in an area.

The method of evaluating irrigation waters proposed by Doneen considers the negligible effects of the less soluble salts in arriving at the total salinity of irrigation waters. The weakness of evaluating waters on the basis of conductivity (or total mineralization) alone is perhaps the most significant development in this paper.

The irrigation water is often the main source of minerals in the accumulation of salts in the soil. The limited solubility of certain chemical constituents in waters is well recognized, with the resulting accumulation of relatively insoluble substances on the lands especially through loss of carbon dioxide. However, highly soluble salts such as chloride (not precipitated or in any way bound in the soil) will pass through the soil if proper drainage exists or may accumulate if no leaching takes place. Declines in soil conditions or improvement therein are directly dependent on leaching (and drainage) that takes place, that is, the salt balance. The latter could be very high or very low contingent upon degree of water application and the effectiveness of the drainage. On the other hand, a measure of movement of highly soluble salts in and out of a given area would not give a true picture as to the degree of accumulation of low solubility salts that remain in the soil which might result in decline of productivity as time goes on. Water management, therefore, may become a dominant factor. The author wisely cautions that the criteria are for general guidance and may be influenced markedly by local conditions such as soil classifications and effective drainage. This is a distinct problem in the irrigation of some new lands in the West, particularly where water of excellent quality is applied to generally thin soils that mantle sedimentary bedrock. Where these soils are high in exchangeable sodium, the chemical composition of the soil solution and drain water from the lands reflect a dynamic condition that cannot be effectively predicated by water-quality criteria alone.

It is generally accepted practice to report electrical conductivity in micromhos ($K \times 10^6$) which is recognized by the author, yet the proposed classification shows conductance units as $K \times 10^5$. Data published by the Geological Survey, as are most other agencies' analyses, are reported in units of micromhos.

The use of the term 'salines' throughout the paper may lead to some confusion especially where Doneen refers to the salts of irrigation water which form 'salines' in the soil. One may infer that salines refer only to the salts which will not be easily precipitated. Perhaps a distinction should be made between those salts which will be precipitated in the early stages of evaporation or through loss of carbon dioxide and the salts which will be left when the water is entirely evaporated.

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A METHOD OF SAMPLING COARSE RIVER-BED MATERIAL

M. Gordon Wolman

Abstract--This determination of the size of material on the bed of a stream is based upon an analysis of the relative area covered by particles of given sizes. The method is applicable to those rivers which flow on coarse material and may be waded during periods of low water. Sampling consists of measuring the intermediate axis of 100 pebbles picked from the bed of the channel on the basis of a grid system. From this sample a frequency distribution is drawn from which the desired size parameters are read. The advantages of the areal sampling procedure over bulk sampling are (1) that it is applicable to very coarse materials, and (2) that it provides a more representative sample of an entire reach of a stream.

Both hydraulic and physiographic studies of rivers often require some measure of rugosity of the channel. To provide an adequate description of bed material, as it affects rugosity, a consistent method of sampling is necessary. The method described here, though applicable only to coarse material, has several advantages over the usual bulk-sample method. The present method can satisfactorily integrate the enormous range in grain size often present in a river bed, as well as the non-random areal distribution of material in pools, riffles, and bars. The author believes this method of sampling described below produces a more representative picture of the bed of the stream, as well as a better measurement of the effective plane of roughness which directly affects the flow within the channel.

Description of sampling method--The determination of grain size is based upon an analysis of the relative area covered by given sizes rather than upon their relative weights. It is essentially an adaptation of suggestions made by J. C. Griffiths, Pennsylvania State University, for obtaining representative samples of heterogeneous materials. These suggestions the author gratefully acknowledges. The method consists of the following steps:

(1) In the desired reach of the stream a grid system is established either by pacing or with actual lines. The size of the grid is determined by the length of reach which the sampler desires to describe. This may include both a riffle and a pool, a riffle alone, or a pool alone. If comparisons are to be made between reaches, the sampler must obviously be consistent in his choice of the length of reach to be included in the sample.

(2) After establishing the grid, which can be done by a pacing traverse as the sampler picks up each pebble, 100 individual pebbles are picked up from the bed. (The sampling is probably less subjective when lines or tapes rather than pacing are used to fix the individual sampling points.) Randomness in the selection of each pebble can only be obtained if the sampler tries not to look at the bed as he picks up each pebble. The author's practice is to draw each pebble from beneath the tip of the toe of his boot.

(3) The intermediate axis of each pebble is measured. The limitations of measuring small individual pebbles such as sand sizes will be discussed below.

(4) Unless the actual diameters are of interest, a rule or scale can be designed showing class limits only and each pebble tallied within a grade class immediately. For this purpose the Wentworth scale is probably the most useful.

(5) With the pebbles placed in the proper classes, it is a simple matter to plot a frequency distribution of the sample. This plot is further simplified if the Wentworth size classes are denoted by the ϕ notation [KRUMBEIN, 1936] in which $\phi = -\log_2$ diameter in mm. Using this logarithmic scale the frequency distribution can be plotted on arithmetic coordinate paper (Fig. 1). Having plotted cumulative frequency curves for the distribution, the median diameter or other desired parameters can readily be determined in the field [INMAN, 1952].

The paragraphs which follow include observations on the present range of the experimental data, a comparison of the results of this procedure with the results produced by other sampling methods, and a brief analysis of the reproducibility of the sample obtained from a given reach by one or more operators.

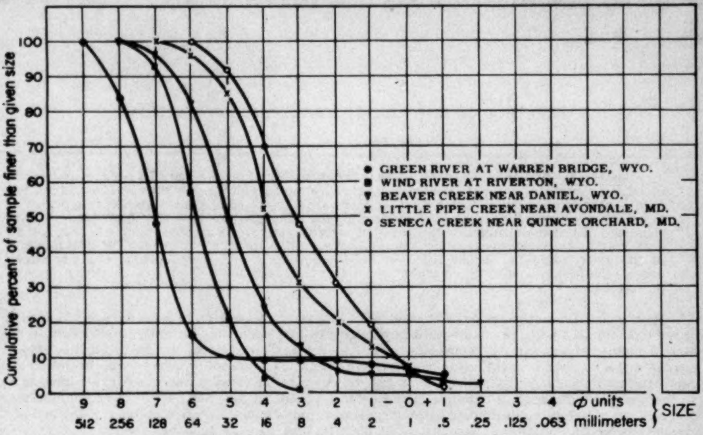

Fig. 1--Size analyses of river-bed gravels

Range of experimental data--The illustrative examples shown in Figures 1 and 2 from a large number of rivers flowing in diverse geographic regions indicate that the cumulative frequency curves of these samples resemble the distributions often shown by river gravels. Figure 2 compares these coarse bed materials with the normally distributed river-bed sands described by BLENCH [1952]. The median diameters of the samples range from 8 to 120 mm. Sorting, as measured by the ϕ standard deviations [INMAN, 1952, p. 135], ranges from 0.85 to 2.95 in the samples studied. These sorting values are lower on the whole than those listed by KRUMBEIN [1942] for comparable (possibly finer) gravels. Although it is conceivable that this method of sampling produces an apparent uniformity in the sample, the range of sorting found in the sediments thus far studied indicates that such a bias, if present, is not significant.

Comparison with other methods of sampling and analysis--It is interesting to compare samples determined from pebble counts with samples of the same material analyzed by sieving and weighing. As the example in Figure 3 shows, although the shapes of the curves are similar, the median diameter of the sample determined by the author's number frequency method is considerably larger than the median diameter of the sieved sample. The consistency of this relationship has been demonstrated by several analyses. The relationship is the reverse of the one we would expect if the comparison consisted simply of counting pebbles versus weighing the amounts of material in each sieve class from precisely the same sample. In the present instance, however, it is apparently the sampling procedure rather than the method of analysis which produces the discrepancy in median grain size.

The sample obtained from the grid represents the areal distribution of material on the bed. Each point sample actually represents a portion of the bed surface. If, for example, the sample of 100 stones contains ten in class 32-64 mm, the plotted frequency distribution actually shows that ten per cent of the surface area sampled is covered by material in the class 32-64 mm.

The distributions in Figure 3, therefore, represent analyses of samples taken from the same reach by two entirely different methods. The difference stems from the fact that the sieved sample represents a scoop of material obtained from one or more locations on the bed. If the bed contains coarse material, to be representative each sample must weigh in the neighborhood of 200-300 pounds. As a rule, in the absence of a dredge capable of obtaining a huge sample covering a wide surface area of the bed, we obtain for sieve analysis a non-representative sample from selected spots which contains a preponderance of fine material. It is the author's opinion that in most instances this defect in sampling is insurmountable if a volumetric analysis is made.

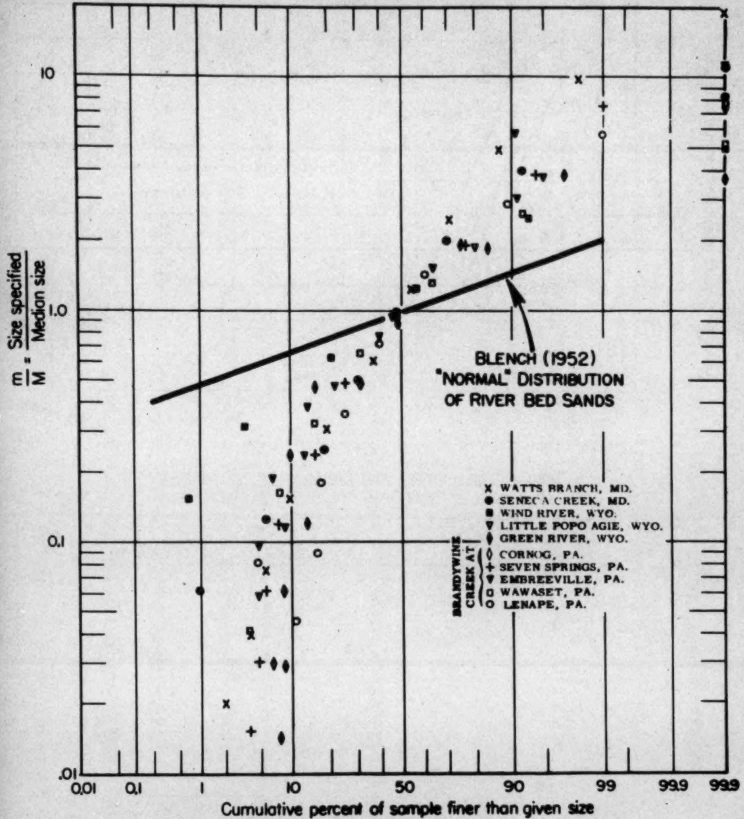

Fig. 2--Dimensionless size distribution for ten samples of river-bed gravels illustrating range of sorting and deviations from a normal distribution

Reproducibility of results--The reproducibility of results of the sampling at a given location is illustrated by the data presented in Tables 1 and 2. The three samples from Watts Branch (Table 1) were taken on separate days by the same sampler. In each case the distribution described by the cumulative frequency curves is much the same, although on one occasion the median diameter was considerably larger than on the other two. In all three samples the variance of the number of particles within the individual grades or size classes showed no systematic variation with grain size. The data from Mines Run (Table 2), a dry channel in a sandstone region in the Shenandoah Valley of Virginia, show the small amount of variation encountered at a given locality when a single operator samples 900 pebbles in groups of 100 pebbles. The standard deviation of the median diameters of these groups of 100 pebbles is 6.7 mm.

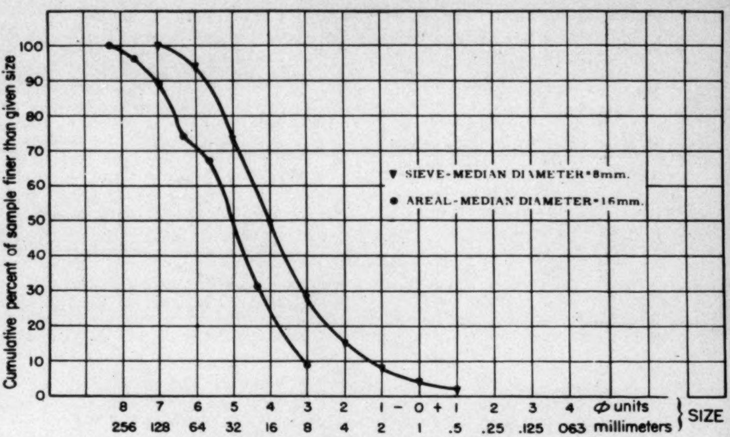

Fig. 3--Comparison of samples obtained from sieve and areal analysis

Table 1--Size distributions of three river-bed samples obtained at Watts Branch near Rockville, Maryland

Size		1953		
mm	φ	June 19	August 25	October 1
0.5	1	....	3	2
1	0	4	0	2
2	-1	5	3	2
4	-2	11	3	4
8	-3	8	5	10
16	-4	8	17	17
32	-5	16	15	17
64	-6	16	26	17
128	-7	17	21	16
256	-8	10	6	11
512	-9	....	1	3
Median diameter, mm	....	25	37	26

In addition to illustrating the reproducibility of the sample, the data from Mines Run (Table 2) also suggest the minimum number of pebbles which should be counted to produce the described result. It can be seen from the table that 100 pebbles was sufficient to describe this distribution. Using the observed standard deviation, Student's t test suggests that one sample of 100 pebbles would be required to obtain a mean median diameter within plus or minus ten mm (12 pct of the median), with a likelihood of being correct approximately two-thirds of the time. Although it is conceivable that in larger rivers a greater number would be desirable, the use of 100 pebbles makes the computation of cumulative percentages and plotting of the distribution in the field extremely easy. Pending evidence to the contrary, this method appears reasonable.

Natural river channels possess small depositional 'provinces' such as occur on bars and riffles or in pools. If there is a distinct difference in the statistical variability of the individual deposits, those having the greater variability should be more intensively sampled than those of less variability

Table 2--Size distribution of nine samples obtained by one sampler from Mines Run, Virginia, July, 1953

Size	B2	B4	B6	B8	OA	A2	A4	A6	A8
mm									
4	1	1	2	2	...	1	1	2	...
10	2	1	2	3	3	3	4	2	...
25	6	11	9	12	14	4	7	9	8
40	8	11	8	7	8	11	11	11	9
63	15	16	16	7	9	18	14	23	17
100	22	22	18	23	26	22	26	13	20
160	19	21	27	21	19	18	15	17	23
250	19	13	14	16	15	17	13	13	12
400	5	3	1	7	4	5	6	4	9
630	3	1	3	2	2	1	2	4	1
1000	...	...	...	...	...	...	1	2	1
Median diameter, mm	94	80	82	84	83	80	79	69	87

Published data on river gravels from these depositional 'provinces,' however, show no marked differences in variability, and hence the random sampling proposed here appears to give the most significant results.

In obtaining samples from Mines Run the grid system was moved upstream and downstream at two-foot intervals in order to determine the effect of minor changes in the position of the grid on the reproducibility of the results. No systematic differences with position were observed, and, as before, the data showed no systematic variation within individual size classes; that is, the error of variation in sampling did not change systematically with change in grain sizes. The data from Watts Branch and from Mines Run suggest that an individual operator can repeat his sampling performance. Whether or not the accuracy of this repetition is sufficient for a given problem depends upon the results desired by the investigator.

The evidence available indicates that the results obtained by different operators on the same reach of channel do not differ appreciably. The three analyses obtained by different samplers from the Wind River at Riverton, Wyoming (Table 3), show extremely little variation in their median diameters and sorting. As the table shows, the median diameters were 51, 49, and 51 mm. The cumulative frequency curves for each of the samples are very similar. Data from Garner Run at Leading Ridge Gap, Pennsylvania, also show the consistent results obtained by different operators (Table 4). Although of limited value, five additional analyses indicate little variation in the results obtained by only two samplers.

Table 3--Size distribution of three samples obtained by different operators from Wind River at Riverton, Wyoming, August 6, 1953

Size		Operator		
mm	ϕ	A	B	C
8	-3	1	0	0
16	-4	4	1	3
32	-5	24	26	38
64	-6	51	56	53
128	-7	50	49	36
256	-8	10	8	10
Median diameter, mm	...	51	51	49

Table 4--Size distributions of three samples obtained by different operators from Garner Run at Leading Ridge Gap, Pennsylvania, September 31, 1953

Size		Operator		
mm	ϕ	A	B	C
2	-1	1	0	0
4	-2	4	0	0
8	-3	1	5	1
16	-4	4	6	4
32	-5	4	3	5
64	-6	16	13	17
128	-7	15	13	16
256	-8	11	13	13
512	-9	4	7	4
Median diameter, mm	...	64	77	77

Within the range of roundness normally encountered in river studies, there is little or no error introduced by the possibility of different samplers measuring different intermediate axes.

Limitations of the sampling procedure--The principal limitation thus far encountered in practice is the inability to measure accurately the fine particles. Two to four mm is about the smallest size which can be measured in the field. When the proportion of fine material is small, the smallest sizes may be lumped together or measured roughly in separate grades. Either system produces little change in the final result. Where fine material predominates, a sampling method such as this, which provides an areal coverage of the bed, requires both a sampler capable of drawing a single or a limited number of grains from the stream bed, and a calibrated magnifying glass which will permit measurements of fine particles in the field.

The difficulty of bed sampling by hand in deep water is a second limitation of the method. Thus far no satisfactory mechanical sampler has been developed for coarse material. The method is workable, however, where the water is several feet deep; and thus the importance of this limitation, which is common to all kinds of sampling beneath flowing water, is at least reduced.

Although it may not be a permanent one, the fact that the areal sampling procedure described here produces results, which are not directly comparable to the results previously obtained by bulk sampling and analysis of samples by weight, is something of a drawback. Additional work along the lines described by MARSCHNER [1953] may make it possible to convert from one system to another. It is important to remember, however, that conversion is only possible, or for that matter useful, where the samples themselves have equal validity. The primary significance of the sampling procedure suggested here is the fact that it gives a more representative sample, and hence a different one from those customarily obtained from river beds.

Conclusion--The principal advantages and disadvantages of the areal sampling procedure described here can be summarized as follows. In its favor are: (1) it is simple to perform, and indeed it is 'possible' in situations where flowing water and coarse material make other methods almost impossible; (2) the sampling method provides a reasonably representative sample of an entire reach of the stream; and (3) a sufficient range of sizes can be measured to permit some standardization of methods, making possible comparison of results obtained in studies of hydraulic roughness in one place with those obtained elsewhere. Its primary disadvantage at present is the inability to handle fine material.

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ESTIMATING THE MANNING COEFFICIENT FROM AN AVERAGE BED ROUGHNESS IN OPEN CHANNELS

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Abstract--The Manning coefficient of roughness in open channels plays an important role in the determination of discharge by slope-area methods. It is not a constant for different depths of flow in a channel, but varies as the depth to the one-sixth power, as well as in some relation to the average height of bed roughness. Through use of the logarithmic velocity-distribution equation for flow in open channel, these relations can be evaluated. When the Manning coefficient is expressed in terms of height of channel roughness, its determination is much simplified in the field as the roughness can be estimated with considerable error without materially affecting the coefficient.

As a second means of determining the Manning coefficient, the distribution of velocity in the vertical at gaging stations provides a useful tool. The logarithmic velocity-distribution equation and the Manning equation can be solved for the Manning coefficient in terms of the ratio of the velocities at two-tenths and eight-tenths the depth. The coefficient thus determined can be used in the computation of main-channel flows following floods that could not be measured by the current meter.

Curves of relation between the Manning coefficient and the ratio of average depth to average height of roughness and between the coefficient and the ratio of the velocities at 0.2 and 0.8 depth are presented.

Introduction

Slope-area determinations are frequently required after great floods occur. It is occasionally not possible to make stream-flow measurements at gaging stations during such floods and it is often desirable to make flow determinations at other reaches along a stream than at a gaging station. For these reasons, it is highly desirable that a reasonably accurate method of determining the coefficient of roughness be at hand.

The slope-area method of measuring the discharge of a stream consists of the determination of three basic factors: the area of the average cross section of a longitudinal reach of channel of known length; the slope of the water surface or the energy gradient in the same reach; and the character of the stream bed, so that a suitable roughness factor may be chosen. The first and second factors can be determined by surveying the channel. The third, which is of equal importance, at present can only be estimated by someone who has a great deal of experience in that field. It is the purpose of this paper to present two methods whereby the channel roughness coefficient may be determined by estimating an average height of roughness or by study of the velocity distribution in the vertical, if a gaging station is maintained on the stream near the site where the slope-area determination is to be made.

The Manning coefficient as a function of bed roughness

The Manning equation for mean velocity--Slope-area determinations of flow in an open channel are usually made through use of the familiar Manning equation

$$V = \frac{1.486}{n} y_o^{2/3} S^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

in which V is the mean velocity in the cross section, y_o is the mean depth, S is the slope of the energy gradient, and n is the Manning coefficient. The mean velocity as determined by this equation can be related to the mean velocity as determined by the logarithmic velocity distribution for turbulent flow in open channels.

Velocity distribution in turbulent flow--Experiments have shown that the velocity distribution in the vertical in a wide channel is proportional to the shear velocity and is a logarithmic function of the depth. ROUSE [1946] gives an equation of relation between the velocity at a point in the vertical in terms of the mean velocity, from which the velocity distribution may be deduced. It is given by

$$v = 2.5\,(gy_oS)^{1/2}\ln(y/y') \qquad (2)$$

in which $(gy_oS)^{1/2}$ is the shear velocity, y is the distance up from the bottom of the channel, and y′ is the distance above the bottom of the channel to the point of zero velocity.

If this equation is integrated with respect to the depth and divided by the depth, the mean velocity in the vertical is found to be

$$V = 2.5\,(gy_oS)^{1/2}\ln(y_o/ey') \qquad (3)$$

in which e is the base of natural logarithms (2.718...). It is interesting to note that the mean velocity according to this equation is found at 0.632 the depth from the surface, slightly over the 0.6 depth used by the United States Geological Survey.

By combining (3) with (1) and solving, the Manning coefficient is found to be

$$n/y_o^{1/6} = \frac{0.105}{\ln(y_o/y') - 1} \qquad (4)$$

If it is possible to express the height y′ in terms of the height of roughness k in (4), the relation between the Manning coefficient and height of roughness is readily determinable.

Relation between y′ and height of bed roughness k--NIKURADSE [1933], in his experiments to determine the effect of roughness on the flow of water in pipes, used sand grains of various diameters, cemented to the inside surface. The diameter of the sand grain he designated as the height of roughness k. He found that for completely developed turbulent flow $y' = k/30$. It is assumed that this proportionality would hold also for flow in open channels. Therefore, if it were possible to measure or estimate the height of roughness in an open channel, y′ could be determined.

Relation between $n/y_o^{1/6}$ and y_o/k--Eq. (4) has been solved and a curve of relation plotted (Fig. 1). Since (4) was developed on the assumption that the channel was very wide, this curve corresponds to a width-depth ratio approaching infinity.

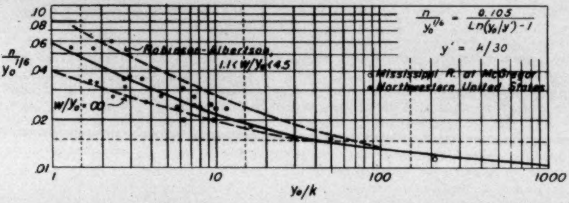

Fig. 1--Relation between Manning coefficient and roughness

ROBINSON and ALBERTSON [1952] have made a study of the Manning coefficient in a small channel, nine inches wide, with depths of flow between two and 8.5 inches and height of roughness of one-half and one inch. The results of their experiments, for ratios of width to depth varying between 1.1 and 4.5, are shown by the upper curve in Figure 1. Since the width-depth ratios are relatively small, it would be expected that sidewall effects might be pronounced. This is verified by the fact that for constant y_o/k ratios this curve lies considerably higher than the curve for infinite width. It would be expected that determinations in natural channels would lie between these curves.

The Manning coefficient in natural channels--The United States Geological Survey has made several determinations of channel roughness in streams in the Northwestern United States. These include measurements of cross-sectional area, width, depth, mean velocity, and slope and computation of the Manning coefficient. The reaches have also been photographed in stereoscopic color and these photographs circulated among the district offices of the Survey as a guide to evaluating the Manning coefficient. These photographs proved an excellent opportunity, albeit second-hand, to examine reaches for which determinations have been made and to estimate the height of roughness. The writer gaged many of these streams some years back and has personal knowledge of their characteristics.

The pictures were examined by the writer and Harlan Schwob of the Iowa District Office of the Geological Survey, each making an independent estimate of the height of roughness. These were averaged. Table 1 contains pertinent data for each of the several streams, including recorded mean depth, estimated height of roughness, the ratio y_o/k, the computed Manning coefficient n, using the field data, and the ratio $n/y_o^{1/6}$. The results of these computations are plotted on Figure 1. Included is one determination on the Mississippi River at McGregor, Iowa, which, while not in the Northwest in the presently accepted geographic connotation, gives a determination with low value of Manning coefficient.

Table 1--Relation between the Manning coefficient and the ratio of mean depth to height of roughness and the velocity-distribution factor for streams chiefly in the Northwestern United States

Location	Mean depth y_o	Height of roughness k	Ratio y_o/k	Manning coefficient n	Ratio $n/y_o^{1/6}$	Velocity ratio $V_{0.2}/V_{0.8}$
	ft	ft				
Yakima River near Umtanum, Washington	11.8	1.0	11.8	0.036	0.024	. . .
	11.8	2.0	5.9	0.036	0.024	. . .
Wenatchee River at Plain, Washington	10.8	3.0	3.6	0.037	0.025	1.36
Chiwawa River near Plain, Washington	5.7	2.0	2.8	0.043	0.032	. . .
Spokane River at Spokane, Washington	14.6	2.0	7.3	0.038	0.024	1.28
Coeur d'Alene River near Prichard, Washington	8.0	1.0	8.0	0.032	0.023	. . .
Middle Fork Flathead River near Essex, Montana	9.1	2.0	4.6	0.041	0.028	. . .
Clark Fork above Missoula, Montana	12.7	2.0	6.4	0.030	0.020	. . .
Clark Fork at St. Regis, Montana	16.3	1.0	16.3	0.028	0.018	. . .
West Fork Bitterroot River near Conner, Montana	4.8	2.0	2.4	0.036	0.028	. . .
Rock Creek Canal near Darby, Montana	1.3	1.0	1.3	0.060	0.057	. . .
South Fork Clearwater River near Grangeville, Idaho	8.9	3.0	3.0	0.051	0.035	. . .
	8.8	2.5	3.5	0.051	0.036	. . .
Boundary Creek near Port Hill, Idaho	4.6	2.5	1.8	0.073	0.057	. . .
Moyie River near Eastport, Idaho	7.3	1.0	7.3	0.038	0.027	. . .
Salmon River at Whitebird, Idaho	20.1	2.0	10.0	0.038	0.023	. . .
Clearwater River at Kamiah, Idaho	19.8	2.0	9.9	0.033	0.020	. . .
Grande Ronde River near La Grande, Oregon	5.4	3.0	1.8	0.043	0.032	1.47
Catherine Creek near Union, Oregon	4.2	1.5	2.8	0.043	0.034	1.42
Rock Creek near Darby, Montana	3.5	1.5	2.3	0.075	0.060	. . .
Blackfoot River near Ovanda, Montana	6.1	1.0	6.1	0.031	0.023	. . .
	1.7	1.0	1.7	0.037	0.034	. . .
John Day River at McDonald Ferry, Oregon	4.7	0.5	9.4	0.032	0.025	1.35
Columbia River near The Dalles, Oregon	50	1.0	50	0.030	0.016	1.30
Mississippi River at McGregor, Iowa	22	0.1	220	0.020	0.012	1.20

Analysis of data--The points of Figure 1 appear to show considerable scatter, but lie in general between the theoretical curve for infinite width and the experimental curve for small width-depth ratios. This would be expected, for while most natural channels are very wide with respect to mean depth, there still is a considerable effect from the channel sides. Also few natural channels are straight and the effect of sinuosity is to increase the apparent roughness. A mean curve has been drawn between the theoretical and experimental curves, averaging the points.

It will be noted that most of the determinations are within 20 pct of the curve, the greatest error being approximately 30 pct. This is considered acceptable in view of the present difficulty in estimating the Manning coefficient by field inspection and comparison with similar reaches with which the observer might be familiar.

The question arises, what is the effect of errors in estimating the height of roughness on determination of the Manning coefficient. Following is an example. If the correct roughness ratio were 10, the coefficient $n/y_o{}^{1/6}$ would be 0.022. If the roughness had been erroneously estimated at twice its true value, the coefficient would be 0.028, an error of approximately 27 pct. The reader can check other values.

The Manning coefficient as a function of velocity distribution

Velocity distribution in the vertical--The measurement of discharge in deep streams is usually accomplished by taking velocity observations in each of several verticals at 0.2 and 0.8 depth. These observations, which are averaged to give the mean velocity in the vertical, can also be used to evaluate the coefficient of roughness. By slight modification, (2) becomes

$$v = 2.5\,(gy_o S)^{1/2}\ \ln \frac{y/y_o}{y'/y_o} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

Substituting for the ratio y/y_o the values 0.2 and 0.8 and solving

$$\ln\,(y_o/y') = (1.61\,R - 0.22)/(R - 1) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

in which R is the ratio of the velocity at 0.2 depth to the velocity at 0.8 depth and is always positive.

Eq. (6) and (4) are combined and a relation between the coefficient $n/y_o{}^{1/6}$ and R, the ratio $V_{0.2}/V_{0.8}$, determined. This is shown graphically in Figure 2.

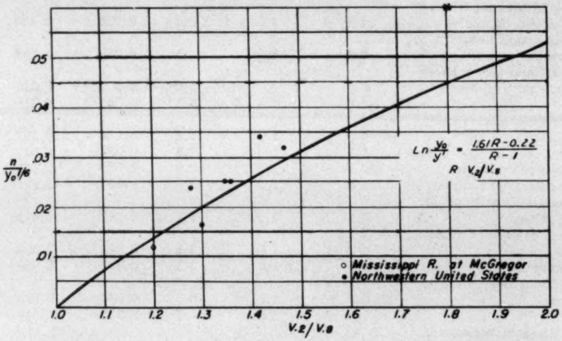

Fig. 2--Relation between Manning coefficient and velocity distribution

Field observations--Three medium and high-stage discharge measurements were analyzed for each of seven of the streams listed in Table 1. The average velocity ratio across the major portion of the channel was computed. The Manning coefficient was plotted against the corresponding ratio on Figure 2.

Conclusions

It would appear that the use of height of roughness as a means of estimating the Manning coefficient for natural channels gives results within acceptable limits of accuracy. It must be realized that not only does the roughness height, but the channel sinuosity as well, have a bearing on the magnitude of the coefficient. The coefficient as obtained by the method described herein would need to be increased if the channel is markedly sinuous. The amount of such increase will need further verification in the field.

It will be noted that as the ratio y_o/k decreases the ratio $n/y_o^{1/6}$ approaches an upper limit of approximately 0.044. Conversely, as the ratio becomes very large, the coefficient approaches approximately 0.010, which might be considered as a lower limit, for very smooth surfaces. It will be noted that a 1000-fold variation in the height of roughness produces a variation in the coefficient of only fourfold.

The method of velocity distribution provides a ready tool for determining the roughness coefficient at gaging stations. This determination will be useful in extending rating curves when current-meter measurements are not possible. There are not sufficient data presented in this paper to precisely delineate the curve of relation (Fig. 2). However, the methods seem to be of sufficient accuracy to warrant further study.

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THE P WAVE AND THE EARTH'S CORE

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Abstract--A study of the travel times of the P wave for recent large-magnitude earthquakes indicates that the P curve is branched, the point of bifurcation occurring at an arcual distance of approximately 90°. From the slope of the earlier portion of the P curve, the depth to the core of the Earth is found to be 2901 km. It is suggested that the later P wave may be one which has traveled to a depth of only 2700 km.

The problem--Seismologists have concerned themselves with a study of the core discontinuity since 1906, when OLDHAM [1906] postulated its existence on the basis of seismic evidence. One of their principal objectives has been the determination of the depth to the core. Three methods have been employed: the determination of the slope of the travel-time curve of the 'diffracted' P wave, the determination of the beginning of the shadow zone of the P wave by a study of the amplitudes, and the determination of the travel time of the reflected core waves, PcP and ScS.

Studies by GUTENBERG [1918], GUTENBERG and RICHTER [1934, 1935], and JEFFREYS [1939b] place the depth of the core at approximately 2900 km. However, there are some variations from this value and certain apparent discrepancies between the various types of data. DAHM [1934], from a study of the travel times of P and PcP, found the depth to the core to be 3000 km, and moreover postulated the existence of a transitional zone. The thickness of this zone was fixed at 220 km, and the average velocity of the P wave through it was found to be 12.57 km/sec. JEFFREYS' [1938] study of distant earthquakes resulted in a value of 4.69 sec/deg for the slope of the 'diffracted' P wave; this would put the core discontinuity at 2570 km depth if one uses JEFFREYS' [1939a] value of 13.63 km/sec as the velocity of P in the mantle immediately above the core. It should be pointed out that Jeffreys did not use the slope of the 'diffracted' P curve but rather the travel times of PcP and ScS to determine the depth to the core. It is also interesting to note that the slope of the 'diffracted' P curve as determined by DAHM [1934] was 4.678 sec/deg. GUTENBERG and RICHTER [1934] have found it to be 4.50 sec/deg. In a more recent study, LEHMANN [1953] suggests that the travel-time curve may have a slight curvature. However, her travel-time relationship is very similar to that of Gutenberg and Richter if one ignores a small constant time difference.

All of the results previously mentioned were based upon the study of earthquakes occurring before 1940. For this reason it seemed profitable to investigate the travel time of P at large epicentral distances using the data of recent earthquakes, since instrumentation, time control, and station density have improved greatly in the past few years.

The data--Large-magnitude earthquakes occurring in the years 1950-1952 for which P was recorded at stations more distant than 100° were used. Only those earthquakes were selected for which a reliable epicenter could be found from the P data for stations nearer than 100°. The JEFFREYS-BULLEN [1948] travel-time tables were used as standards in determining the epicentral coordinates, the origin time, and the depth of focus.

Ten earthquakes were found which satisfied these specifications. They are listed in Table 1, which also includes the computed epicentral quantities.

The actual data consisted of the arrival times of the P waves from these earthquakes for all stations beyond 100°. These arrival times were obtained from the original seismograms of the St. Louis University group of stations and from the reports of other stations, as presented in station bulletins and the monthly bulletin of the Bureau Central International de Séismologie. There were 152 travel times of P beyond 100° available.

In order to use the data of earthquakes of different focal depths in constructing one travel-time curve, it was necessary to reduce the earthquakes to a common focal depth. The depth chosen was 0.000R, corresponding roughly to the depth of the Mohorovicic discontinuity. Since the slope of the P curves just beyond 100° is the same for all focal depths, the method of reduction of the data

Table 1--Earthquakes selected for study

Date	Origin time, GMT	Geocentric latitude	Longitude	Focal depth	Magnitude[a]
1950	h m s	°	°	R	
July 29	23 49 06	6.5 S	155.1 E	0.005	7.1
August 14	22 51 25	27.2 S	63.0 W	0.091	7 1/4
August 15	14 09 35	28.5 N	96.5 E	0.000	8.6
October 8	03 23 12	3.8 S	128.3 E	0.000	7.6
December 2	19 51 52	18.2 S	167.0 E	0.005	7 3/4
December 9	21 38 48	23.6 S	67.6 W	0.010	8.0
1951					
February 17	21 07 11	7.0 S	146.1 E	0.025	7 1/4
1952					
February 11	07 01 06	5.5 S	110.1 E	0.100	7
March 19	10 57 14	9.5 N	127.0 E	0.000	7 3/4
July 13	11 58 37	18.4 S	169.1 E	0.040	7

[a] All magnitudes determined by Pasadena.

consisted in adding to the travel time of the P wave the difference between the travel times of the P wave of the earthquake of given focal depth and that of 0.000R depth at 100° epicentral distance, as obtained from the JEFFREYS-BULLEN [1948] travel-time tables. The corrections were made to the nearest one-half second.

The travel-time curves--All the travel times were plotted as a function of epicentral distance on a large-scale graph. The result was surprising. With the exception of 26 points, the plotted points appeared to define two straight lines. These lines diverged with increasing epicentral distance. Most of the anomalous travel times could be explained by assuming that they were the deep-focus phases, pP or sP.

The slopes of these two curves were determined by the method of least squares. Only travel times beyond 110° were used in these computations because at lesser distances there is such a slight separation between the curves that it was impossible to assign the points definitely to either one of the two curves. The data used for the computations are given in Table 2. The abnormally late arrival times previously mentioned are not included in this table. The symbols P and P_2 refer to the waves corresponding to the first and second P curves, respectively.

By constraining the P curve to pass through the point 13m 43.1s at 100° (from the JEFFREYS-BULLEN [1948] travel-time tables), the slope of the curve was found to be 4.439 ± 0.033 sec/deg. This compares somewhat favorably with a value of 4.50 sec/deg found by GUTENBERG and RICHTER [1934]. The slope of the P_2 curve was determined as 4.688 ± 0.039 sec/deg and its time intercept at 100° as 13m 44.4s. The slope of this curve is practically identical with that given by DAHM [1934] and by JEFFREYS [1938] for the slope of 'diffracted' P, that is, 4.678 and 4.69 sec/deg, respectively. It is suggested that the travel times obtained by Dahm and Jeffreys did not correspond to the actual P wave but rather P_2, and thus any conclusions drawn from these data concerning the depth to the core would be invalid.

There is some evidence in the literature of the existence of the P_2 wave. GUTENBERG and RICHTER [1934] published tentative travel times for 'late' P phases at great distances. MACELWANE's [1930] study of the South Pacific earthquake of June 26, 1924, gives the arrival times of P for very large epicentral distances. If one modifies his origin time so that the P waves at near stations satisfy the JEFFREYS-BULLEN [1948] travel-time tables, one finds that some of the arrival times of the waves which he identified as P agree with that which would be expected of P_2, and that some of the waves which he identified as P? correspond to the expected arrival times of P. The results are given in Table 3.

After the slopes of the two P curves had been determined, the author sent a request to the South American stations for copies of their seismograms of the great Assam earthquake of August 15, 1950, in order to see if both phases were recorded. Seismograms were obtained from Bogota

Table 2--Data for P curve beyond 110°

Earthquake of	Station	Epicentral distance	Observed		Depth correction	Reduced	
			P - H	P_2 - H		P - H	P_2 - H
1950		°	m s	m s	s	m s	m s
July 29	Florissant	113.1	14 37		4	14 41	
	St. Louis	113.2	14 39		4	14 43	
	Cincinnati	117.5		15 00	4		15 04
	Bogota	131.0		16 08	4		16 12
August 14	Ksara	111.6		13 36	61		14 37
	College	112.3	13 37		61	14 38	
August 15	Cleveland	110.2	14 28		0	14 28	
	State College	110.7		14 35	0		14 35
	Cincinnati	112.5	14 39		0	14 39	
	Washington	112.5	14 39		0	14 39	
	Florissant	112.6	14 40		0	14 40	
	St. Louis	112.8	14 40.5		0	14 40.5	
	Tucson	114.1		14 48	0		14 48
	Bermuda	116.7	14 54		0	14 54	
	Miami	125.6	15 33		0	15 33	
	San Juan	130.2	15 55		0	15 55	
October 8	Tinemaha	111.0		14 37	0		14 37
	Haiwee	111.4		14 39	0		14 39
	Pasadena	111.6		14 38	0		14 38
	Rome	111.7		14 40	0		14 40
	Stuttgart	111.8	14 37		0	14 37	
	Firenze-Xim.	112.0		14 40	0		14 40
	Riverside	112.3	14 39		0	14 39	
	Zurich	112.7		14 44.5	0		14 44.5
	Strasbourg	112.8		14 46	0		14 46
	Boulder City	114.0		14 51	0		14 51
	Tucson	118.1		15 11	0		15 11
	St. Louis-Z	130.8	16 00		0	16 00	
	St. Louis-N	130.8		16 10	0		16 10
December 2	St. Louis	111.0		14 35	4		14 39
	La Paz	115.7		14 54	4		14 58
December 9	Riverview	111.9	14 27		7.5	14 34.5	
	Ksara	113.6		14 42	7.5		14 49.5
	Brisbane	115.8	14 48		7.5	14 55.5	
	Perth	124.5	15 26		7.5	15 33.5	
1951							
February 17	Grahamstown	110.0		14 13	19		14 32
	Ksara	110.7	14 12		19	14 31	
	Helsinki	111.3	14 14		19	14 33	
	Lubbock	112.3		14 21	19		14 40
	Helwan	115.0		14 36	19		14 55
	St. Louis	120.5	14 55		19	15 14	
1952							
March 19	Alger University	110.2		14 33	0		14 33
	Tucson	111.0		14 34	0		14 34
	Toledo	113.1		14 44	0		14 44
	Tamanrasset	114.3		14 51	0		14 51
	Palisades	126.1		15 43	0		15 43
July 13	Palisades	122.2	14 53		22	15 22	

Table 3--Travel times of South Pacific earthquake of June 26, 1924

Station	Distance	Macelwane's phase	Arrival time	Arrival time - H	P - H	P_2 - H
	°		h m s	m s	m s	m s
Bombay	102	P	1 51 29	13 54		13 54
Simla	109.5	P	1 52 06	14 31		14 29
Mazatlan	113.3	P	1 52 04	14 29	14 42	
Pasadena	116.2	P	1 52 19	14 44	14 55	
Berkeley	117.1	eP	1 52 39	15 04		15 04
Victoria	124.8	eP	1 53 12	15 37		15 41
Helwan	134.4	eP	1 54 10	16 35		16 26
Sverdlovsk	136.5	eP	1 54 12	16 37		16 36
Chicago	138.2	eP?	1 54 13	16 38	16 33	
Ottawa	146.7	eP	1 54 37	17 02	17 10	
Budapest	152.3	eP?	1 55 09	17 34	17 35	
Strasbourg	159.0	eP	1 55 58	18 23		18 21
Paris	162.0	eP	1 56 00	18 25	18 18	
Uccle	162.1	eP	1 56 10	18 35		18 36
De Bilt	162.3	eP	1 56 11	18 36		18 36
Oxford	165.6	eP	1 56 33	18 58		18 52
Dyce	168.9	P?	1 57 15	19 40		19 07

and Chinchina, both at an epicentral distance of 145.7°, and from Huancayo at a distance of 161.8°. The expected arrival times at Bogota and Chinchina of P and P_2 were 14h 26m 41s and 14h 26m 54s respectively. At Huancayo P should arrive at 14h 27m 52s and P_2 at 14h 28m 09s.

The records obtained from Bogota were from a short-period Benioff vertical, two long-period Sprengnether horizontals, and a Wiechert horizontal. The record of the Benioff vertical was so disturbed by microseisms that it was impossible to identify any phases before PKP. The records made by the Sprengnether horizontals were also disturbed by microseisms. However, on the N-S component there is a suggestion of P_2 at 14h 26m 54.5s, characterized by a gradual downward motion of the trace. The time control is excellent, since a time signal was placed on the records at 14h 00m GMT. Figure 1 shows a magnified portion of the N-S component Wiechert record. The beginning of P at 14h 26m 39.5s is very sharp when viewed under a high-power magnifying lens. No P_2 phase can be identified on this record.

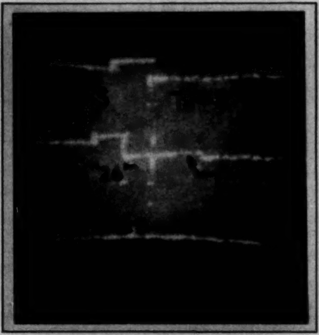

Fig. 1--Bogota Seismogram of August 15, 1950

The instruments in operation at Chinchina are a short-period Sprengnether vertical and two long-period Sprengnether horizontals. Portions of these records are shown in Figure 2. On the vertical-component record P_2 occurs at 14h 26m 56.5s and may be identified by a slight swell in the trace. P_2, at 14h 26m 54.5s, is very clear on the N-S component; and there is a slight suggestion of P, although this may be very possibly due to microseisms. On the E-W component the beginning of P_2 at 14h 26m 55.5s is marked by a persistent downward motion of the trace. There are also time signals on the Chinchina records.

P and P_2 are also difficult to identify on the Huancayo records because of microseismic activity. On the N-S component record there are changes in the motion of the trace, although not in amplitude, at 14h 27m 51s and 14h 28m 08s. Similar changes occur on the E-W component at 14h 27m 51s and 14h 28m 10s. On the vertical-component, short-period Benioff record there is a long-period disturbance at 14h 28m 10s.

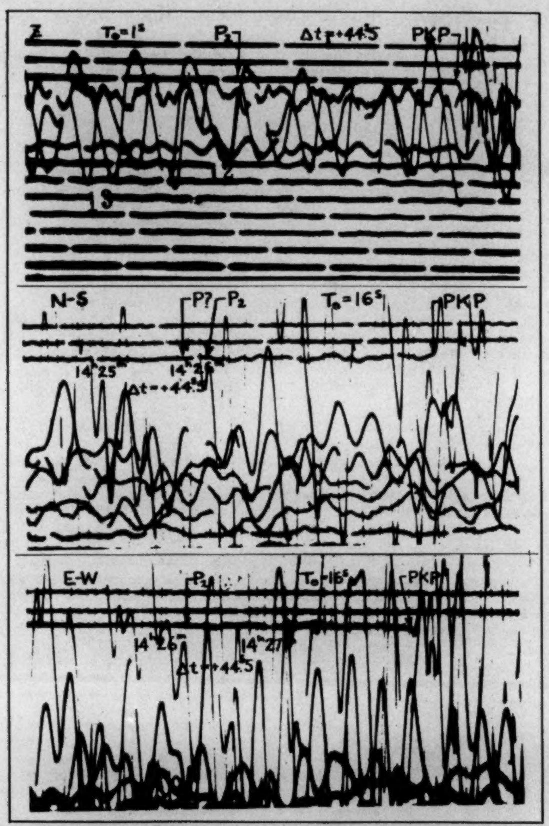

Fig. 2--Chinchina seismogram of August 15, 1950

Conclusions and hypotheses--Using the slope of the P curve and 13.63 km/sec as the velocity of P in the mantle immediately above the core discontinuity, the radius of the core is found to be 3470 km. This would result in a value of 2901 km for the depth of the core below the surface of the mean sphere. Changing the value of the velocity to 13.62 or 13.64 km/sec would change the depth only to 2904 or 2899 km, respectively.

Any statements concerning the structure of the Earth which are based upon the P_2 wave must at present be considered as tentative because of the scant number of observations of the wave. From a limited number of observations, the author has the impression that P_2 is best recorded by short-period vertical seismographs, whereas P at large distances is more likely to be recorded by a long-period vertical. It also appears that P is recorded at distance only for shocks of very large magnitude, whereas P_2 may be recorded at the same distances for earthquakes of smaller magnitudes.

Table 4--Travel times of P and P_2 from 100 to 140°

Distance	P		P_2	
°	m	s	m	s
100	13	43.1	13	44.4
102	13	52.1	13	53.8
104	14	00.9	14	03.2
106	14	09.7	14	12.5
108	14	18.6	14	21.9
110	14	27.5	14	31.3
112	14	36.4	14	40.7
114	14	45.2	14	50.0
116	14	54.1	14	59.4
118	15	03.0	15	08.8
120	15	11.9	15	18.2
122	15	20.8	15	27.5
124	15	29.6	15	36.9
126	15	38.5	15	46.3
128	15	47.4	15	55.7
130	15	56.3	16	05.0
132	16	05.1	16	14.4
134	16	14.0	16	23.8
136	16	22.9	16	33.2
138	16	31.8	16	42.5
140	16	40.7	16	51.9

In JEFFREYS' [1939a] determination of the velocity-depth relationship of the P wave, there is a suggestion that the velocity may decrease very slightly with depth somewhat above the core from a value of 13.65 to 13.61 km/sec. LEHMANN [1953] has pointed out that a slight decrease of velocity with depth would permit a ray containing only a small amount of energy to propagate to great distances without penetrating much deeper. In her words: "P waves are sometimes observed at much greater distances than 130°. They may be direct, but with a decrease of velocity slightly smaller than the critical one, for which $d(r/v)/dr = 0$, P waves of small energy will be transmitted to great distances without penetrating much deeper."

A velocity decrease from 13.65 to 13.61 km/sec occurring at a depth of 2700 km as obtained from the slope of P_2 would have to take place in a zone no thicker than ten km in order that $d(r/v)/dr \leq 0$.

If we for the moment accept that P_2 is a wave which penetrates no deeper than 2700 km, then the backward extension of its travel-time curve should intersect the P curve at a distance corresponding to that traveled by a P wave which has penetrated 2700 km below the surface of the Earth. From JEFFREYS' [1939a] velocity-depth tables we find this distance to be approximately 90°. In fact, the extrapolated travel time of P_2 at 90° for 0.000R focal depth is 12m 57.5s. From the JEFFREYS-BULLEN [1948] tables, the travel time of P at 90° is 12m 57.4s.

Table 4 presents the travel times of P and P_2 for earthquakes of normal focal depth from 100 to 140°.

Acknowledgments--This paper is based on a portion of a dissertation presented to the faculty of the Graduate School of St. Louis University in partial fulfillment of the requirements for the degree of Doctor of Philosophy, 1953. The author wishes to express his thanks to J. E. Ramirez, S. J., who loaned him the seismograms of the Bogota and Chinchina stations for August 15, 1950, and to Beno Gutenberg who forwarded copies of the Huancayo records for the same date. In particular he wishes to acknowledge the assistance of James B. Macelwane, S. J., who suggested and directed this work, and whose valuable suggestions, criticisms, and encouragement made the completion of this work possible.

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SEISMIC WAVE VELOCITIES IN WESTERLY GRANITE

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(Publication No. 50, Institute of Geophysics, University of California)

Abstract--A precision laboratory measurement of the principal wave velocities in a homogeneous material is presented as evidence that a closer agreement may be obtained between laboratory and field results than heretofore thought possible. The laboratory results differ from field quantities in a predictable direction. The method is an application of laboratory techniques in an imitation of field procedures to a scale model of field structures.

This paper describes a laboratory method for determining the velocity of elastic waves in rocks. The procedure used here is essentially the same as that commonly used in field seismology. Time-distance relationships are plotted from the observations of the several arrivals; the wave velocities are then obtained from the slopes of the time-distance curves.

The specific material tested was a block of Westerly, R. I., granite (obtained from the Sullivan Granite Company, Westerly, R. I.) of dimensions 37 × 37 × 27 cm. This granite is a fresh, fine-grained, blue-white specimen, free of flaws and of mean specific gravity 2.66. One of the surfaces (37 × 37 cm) is highly polished and it was upon this surface that all measurements were made. All experimental data were taken at room temperature and one atmosphere of pressure.

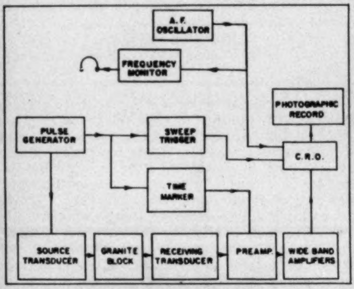

Fig. 1--Schematic diagram of experimental arrangement

The experimental arrangement is shown schematically in Figure 1. The excitation of the granite was obtained from a 1/4-inch cube stack-of-six lithium sulfate monohydrate (LH) crystals of the type described by BERANEK [1949]. The crystal stack was placed in direct contact with the polished granite surface and excited by a square voltage pulse of 2.5-microsec duration. Since only first arrivals were to be studied, the only requirement placed upon the excitation wave form was that the rise time be of short duration. The rise time of the voltage pulse used was of the order of 0.5 microsecond.

Detection of the surface motion was achieved through the use of another LH crystal element similar to that described above. Both the receiver and source crystal elements were unsupported on the faces away from the load and both were coupled to the load by a thin film of castor oil. The receiver crystal was underdamped and possessed a resonant frequency lower than the principal frequency components of the incident waves. These characteristics enhance the sharpness of the records and thus favor the precise determination of arrival times.

The received signal was amplified and observed upon the face of an oscilloscope. The source was pulsed at a fixed repetition rate of 1000 cps. The source voltage pulse also triggered the sweep of the oscilloscope and provided an initial time mark on the records. The trace was photographed at long exposures (f/4 up to five seconds), and the sharpness of typical results (Fig. 2) testifies to the reproducibility of the wave forms under repetitive excitation.

The experimental observations (Fig. 2) were made at successive receiver stations located 0.5 cm apart, 1.0 to 12.5 cm from the source. Distances between the nearest edges of the two crystals were recorded. Successive traces on the record were taken at 0.5-cm increments in source-receiver separation. The time scale used in these measurements is approximately 12 microsec between the small time markers on the records. The effects of nonlinearity in the sweep rate and other nonlinearities in the time base of the record, such as curvature of the oscilloscope tube face, and the distortion in the camera field, were all eliminated simultaneously by a sweep calibration with a crystal-controlled, 200-kilocycle, sine wave signal.

Readings of the arrival times of the two direct waves were made from the 35-mm film record with a measuring microscope. The results are plotted in Figure 3. The slower wave is later identified as a Rayleigh wave. The slopes of the straight lines passed through the data yield as the velocities of the P- and R-waves the values

$$\alpha = 5.76 \pm 0.06 \text{ km sec}^{-1}$$

$$\gamma = 2.98 \pm 0.01 \text{ km sec}^{-1}$$

(The ± values presented for these and succeeding quantities are probable errors.) From the velocity ratio

$$\gamma/\alpha = 0.518\ (1 \pm 0.009)$$

the Poisson ratio may be computed [KNOPOFF, 1952]

$$\sigma = 0.270 \pm 0.007$$

The apparently negative value of the intercept on the range axis in the time-distance curves for both the P- and R-waves has been traced to a time delay in the receiver amplifier circuits and is not a real effect. The true origin for the time coordinate is indicated in Figure 3 and corresponds to an amplifier delay of approximately three microseconds.

The slow wave is identified as a Rayleigh wave upon the basis of predictions for the impulsive problem made by LAMB [1904]. The normal component of the S-wave is small compared with P and is masked by R which already exists in considerable amplitude at the instant of onset of S. However, the Rayleigh wave is a slowly varying function until a time close to the instant of violent amplitude reversal, r/γ. Thus the S-wave is easily lost in noise or in the oscillatory tail of the P-wave. The early part of the Rayleigh wave cannot excite the high-frequency resonant crystal but this is readily accomplished at times close to the instant of displacement reversal, yielding a strong receiver burst at the time r/γ.

It is of interest to note that, had the second wave been interpreted as S, the Poisson's ratio computed for the velocity ratio

$$\beta/\alpha = 0.518\ (1 \pm 0.009)$$

would have been

$$\sigma = 0.318 \pm 0.005$$

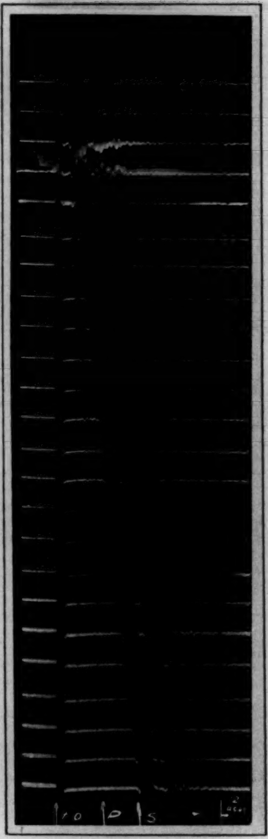

Fig. 2--Trace of experimental observations

This value is in coincidental agreement with the field observations of LEET and EWING [1932] and LEET [1933] upon other granites from this region. Leet and Ewing and Leet obtain

$$\sigma = 0.31 \text{ to } 0.33$$

It is further noted that the amplitude data for the slow wave group yields no direct information concerning the identity of the arrival. Although the amplitude of this wave group varies as $r^{-0.5}$, a value predicted for Rayleigh waves, the peak of the signal occurs after the arrival of both the S- and R-wave fronts, if both are in evidence. It is known [LAMB, 1904] that no resolution of the S-

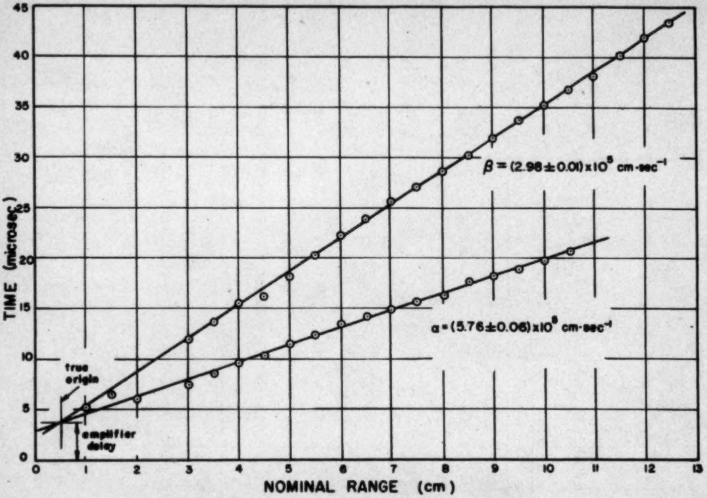

Fig. 3--Arrival times of two direct waves

and R-waves is possible in this problem.

The errors in the velocity measurements may be separated into two groups: those arising from imperfections in calibration of the 200-kc frequency standard, and those of experimental scatter in the positioning of the pickup and in the reading of arrival times. The computation of Poisson's ratio is affected only by the errors in reading arrival times and in receiver positioning. Quantitative evaluation of the velocities and probable errors due to scatter were made by least squares. The probable errors in the determination of the P- and S-velocities are about one and 0.3 pct respectively. The associated error in computing Poisson's ratio is about two per cent. The accuracy of the LM-14 frequency monitor was better than 0.1 pct and thus the sweep calibration errors have been neglected in comparison with the more significant errors due to experimental scatter.

The elastic properties of samples of Westerly granite have been measured by other methods in the laboratory by ADAMS and COKER [1906], ADAMS and WILLIAMSON [1923], IDE [1936], and BIRCH and BANCROFT [1938] and in the field by LEET and EWING [1932]. These results may be compared with the corresponding present laboratory values obtained for the velocities and the elastic constants computed therefrom (Table 1). In three of the earlier papers, values were given for only two of the three fundamental elastic parameters. In these cases reasonable assumptions for the value of the missing parameter were made, and the secondary quantities computed therefrom. In the case of the Leet and Ewing and the Birch and Bancroft measurements, two sets of assumptions for the Poisson's ratios were made. The value $\sigma = 0.33$ is chosen in view of Leet and Ewing's measurement upon the Quincy granite. The value $\sigma = 0.27$ is the value obtained in our measurements.

It will be noted that our values of velocities and moduli are consistently higher than all of the earlier measurements. It is significant that the present laboratory measurements lead to excellent agreement with the value of Poisson's ratio obtained by Adams and Coker in the laboratory and by Leet and Ewing and Leet in the field for similar granites. The overall failure of the earlier laboratory measurements to agree with the field values of the moduli and velocities has been acknowledged by ZISMAN [1933], Ide, and Birch and Bancroft. To explain the discrepancy it was

Table 1--Elastic constants and velocities for Westerly granite

Item	Symbol and units	Adams and Coker	Leet and Ewing		Ide	Birch and Bancroft		Present values
			$\sigma = 0.33$	$\sigma = 0.27$		$\sigma = 0.33$	$\sigma = 0.27$	
P-wave velocity	α, km sec^{-1}	4.71	5.00^{ab}		3.80	4.52	4.06	5.76 ± 0.06^{a}
S-wave velocity	β, km sec^{-1}	2.82	2.52	2.80	2.68	2.28		3.23 ± 0.02
R-wave velocity	γ, km sec^{-1}	2.61	2.35	2.58	2.37	2.13	2.10	2.98 ± 0.01^{a}
Density	ρ, gm cm^{-3}	2.616^{ad}	2.64^{a}		2.64^{c}	2.64^{a}		2.658 ± 0.004^{a}
Compression modulus	$\lambda + 2\mu$, 10^{11} dy cm^{-2}	5.81	6.60		3.81	5.40	4.35	8.82 ± 0.18
Shear modulus	μ, 10^{11} dy cm^{-2}	2.08	1.67	2.08	1.89^{a}	1.37^{a}		2.77 ± 0.04
Young's modulus	E, 10^{11} dy cm^{-2}	5.10^{a}	4.45	5.28	3.99^{a}	3.64	3.48	7.04 ± 0.10
Bulk modulus	k, 10^{11} dy cm^{-2}	3.03	4.36	3.83	1.50	3.57	2.52	5.13 ± 0.19
Compressibility	1/k, 10^{-12} cm^{2} dy^{-1}	3.30	2.29	2.61	6.68	2.80	3.97	1.95 ± 0.07
Poisson's ratio	σ	0.2915^{a}	0.33^{c}	0.27^{c}	0.056	0.33^{c}	0.27^{c}	0.270 ± 0.007

[a] Fundamental measurement.

[b] ± 0.04.

[c] Assumed value; these assumptions correspond to models for which the remaining constants may be computed.

[d] Taken from ADAMS and WILLIAMSON [1923] who used the same sample.

Note: Unmarked numbers are secondary quantities computed from the fundamental measurements and the assumptions.

suggested that the laboratory specimens were under insufficient pressure to close cracks and flaws in the specimen; furthermore, under the stresses necessary to produce measurable strains in the laboratory, the elastic limits may have been exceeded in the small specimens. In our experiments the latter difficulty did not exist; the strains in the present experiment are an order or more of magnitude smaller than those in the early static and dynamic experiments.

The values most closely approaching the present measurements are the field data of Leet and Ewing. Measurements made in the laboratory upon a specimen free from flaws should yield moduli and velocities exceeding those obtainable from a cemented, faulted specimen. No evidence for dispersion exists in this material so that it is not anticipated that velocity differences between the field and laboratory computations are due to the frequency differences involved.

Acknowledgments--The author wishes to thank D. T. Griggs for suggesting the material upon which these measurements were taken and to express appreciation to him and to R. J. Uffen for helpful discussion of the results. Further acknowledgments are due L. B. Slichter and M. N. Jarabin for reading the manuscript and offering suggestions thereupon, and to G. L. Brown for assisting in the actual experiments.

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REPORT OF THE COMMITTEE ON CHEMISTRY OF NATURAL WATERS, 1952-1953

W. W. Hastings, Chairman

Bruce F. Beacher Frank M. Eaton Otto M. Smith
Eugene Brown Russell M. Jeffords Herbert A. Swenson
L. D. Doneen Nicholas A. Rose Paul Weaver

Introduction--The activities during the year of the individual Committee members working in their own lines of specialization embraced practically all fields of water chemistry. However, the interests of the group were primarily focused on the problem of water quality as related to irrigation agriculture.

This report of the Committee consists largely of a special paper relating to problems associated with judging water quality in irrigation agriculture prepared by one member of the Committee, L. D. Doneen. This report was circulated among the membership for discussion. Doneen's paper, together with discussion by several members of the Committee, appears on pages 943 to 950 of this issue of the Transactions.

Doneen's paper is most timely as the classification of irrigation water is an ever-present problem in western agriculture. He has suggested a new standard for classifying irrigation waters based on the 'effective salinity,' and he discusses the application of this standard to irrigation agriculture. Consequently, his paper should provoke some discussion by scientists in this field.

Also, several members of the Committee have prepared brief reports on their activities in the field of water chemistry. Their statements follow this introduction. The Chairman is deeply indebted to all who so willingly contributed their time and efforts to prepare material for this report.

Paul Weaver (Gulf Oil Corporation, Houston, Texas)--With respect to some general comments concerning connate waters, generally such waters increase in salinity with depth below the surface. Also they may have essentially the overall characteristics of sea water, but even the youngest and shallowest of them, as in the Coastal area of Louisiana, show an important change compared to sea water. In the first place, calcium is usually present in excess of magnesium, sometimes as much as three times as much magnesium, whereas in ocean water the relationship is reversed. Secondly, although there is poor documentation because of disregard in analysis, the potassium content is quite small compared to sodium and even smaller than in ocean water. These differences remained unexplained for many years, but in recent times there has been a very considerable body of information which suggests the cause of such alterations.

It has been found that clay minerals brought in by the rivers to the ocean and to lagoons along the seacoast undergo very rapid modifications. The predominant montmorillonite in river waters changes to illite and finally to chlorite by base exchange and removal and addition of magnesium and potassium which, of course, has come from the water. Cation replaceability of clay materials has been discussed by GRIM [1942]. This process has been observed in some coastal waters. The clay particles in sands are quite common in oil fields and are overlain and underlain by clay beds in most cases.

In a recent communication, Ralph E. Grim (Department of Geology, University of Illinois, Urbana, Illinois) furnished the following comments on this subject:

> I am convinced that illite and chlorite are formed in sediments accumulating in a marine environment as a consequence of changes taking place in sediments brought to the sea by rivers. The change in many cases has been from montmorillonite to illite or chlorite, but it seems likely that these later clay minerals can form from other parent material in a marine environment. Montmorillonite is not always the dominant clay mineral in river sediments.
>
> The formation of illite and chlorite in the marine environment, of course, involves the pick-up of potassium and magnesium, and it seems to me that there is no doubt that this is a major explanation for the differences in the relative abundance of potassium, magnesium, sodium, and calcium in various types of waters.

We here have done a considerable amount of work on this subject, and some of our publications go into it in some detail. The literature contains considerably additional data, much of which is summarized in my book, Clay Mineralogy. The evidence comes not only from clay mineral studies themselves, but from other studies such as theoretical considerations of the structure of the clay minerals, laboratory syntheses investigations, and cation exchange studies.

We have been investigating accumulations along the Texas Coast of the Gulf of Mexico and have a publication about ready on this subject. In this area it seems to me there is clear evidence for the formation of chlorite and illite in the marine environment. We have attempted to make a study of the cation composition in waters in immediate contact with the sediments, and the data definitely require the pick-up of potassium and magnesium by the sediments.

It also seems to me that the evidence is quite strong that the formation of illite and chlorite takes place quite quickly when the fresh water sediments reach the marine environment. It seems to me that the transition is almost contemporaneous with accumulation.

Reference

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B. F. Beacher (U. S. Bureau of Reclamation, Washington, D. C.)--Anticipating and forecasting the quality and suitability of surface and ground waters for irrigation use have become increasingly important in the planning, construction, and operation of large-scale Federal irrigation projects. In one instance of a Missouri River tributary in South Dakota, the forecast of water quality was unfavorable enough to preclude irrigation development. In another instance in Montana, the water quality and salt-balance situation will largely determine project success. A special program for control and use of water must be followed in the latter case to sustain production under the soil, water, and drainage conditions which are anticipated. Many other irrigation projects have been undertaken recently with or without qualification as to water quality, but in all cases a prognosis of quality is attempted. What procedures are used and what problems commonly are encountered?

Present procedures for forecasting water quality have been developed on the basis of experience and applicable research [U. S. BUREAU OF RECLAMATION, 1950a]. For example, the special procedure followed in the case of the South Dakota tributary of the Missouri River is generally applicable where storage of surface runoff in semiarid or arid regions is planned. The waters will be used for irrigation on previously undeveloped lands, including return flow waters from upper portions of the area to lower lying lands, and downstream use of the water is expected [U. S. BUREAU OF RECLAMATION, 1950b]. The initial requirement was for basic hydrologic data showing stream discharge at several stations through the area over a reasonably significant period of time (in this case 20 years), chemical analysis of water samples taken at the stations, physical and chemical characteristics of the lands proposed for irrigation, climatological data, and the preliminary engineering plans for the project. A series of water-supply studies with various reservoir operations was made to determine the maximum acreage that could be served with the storage available and the reservoir releases which would be necessary to dilute the return flows for downstream use. The quality studies were divided into two main parts: (1) quality of water in the reservoir, and (2) quality of water progressively downstream as it was used for irrigation. The first part dealt with the extent of mixing of the salts in the reservoir from the inflows and floods, uniformity of the total dissolved solids in solution in the reservoir, effect of evaporation and solution, concentration of releases to irrigation, and concentration of spills. Concentration curves were developed for calcium, magnesium, sodium, and potassium ions with relation to mean daily stream discharge in second-feet. The concentrations in tons of ions and total dissolved solids for reservoir inflow and outflow each month then were computed. A reservoir operation table was prepared showing for each year the monthly and periodic releases. In the second part of the studies, the area downstream from the reservoir was divided into significant reaches; and the anticipated diversions, return flow, and natural accretions were computed for each reach on a monthly basis. Many assumptions were necessary for the computations concerning the changes in water quality after application to the lands and the probable return flow characteristics of the area. The percentage of sodium and total dissolved solids in the stream supply at the end of each reach every month were estimated. Probable salt-balance and crop-production conditions on the various lands in the area were forecasted, and questionable tracts were excluded.

The problems commonly encountered in accomplishing procedures of this type relate mainly to the interpretation of the data. The general practice in developing interpretations of water quality for irrigation has been to use the quality criteria which have been offered within recent years, such as those outlined by WILCOX [1948ab], THORNE and THORNE [1951], and EATON [1950]. The limitations and specific applicability of the criteria are not well defined. General application of criteria by interpreters may occasion erroneous conclusions. For example, water containing about 30 epm total soluble salts generally is labeled unsuitable for irrigation, yet there are positive advantages in the use of saline irrigation water in the reclamation of alkali soils [see KELLEY, 1951]. The criteria favor waters of low concentration, but undesirable increases in lime in certain Utah soils occur with the use of waters fairly low or moderate in salt content [see THORNE and THORNE, 1953]. BODMAN and FIREMAN [1950] show that reduction of permeability is most severe when irrigation with salt-free water follows irrigation with saline-alkaline waters. As pointed out by CHRISTENSEN and LYERLY [1952], probably too much emphasis has been placed in attempting to answer the question "How good is this water?" rather than "What can be done with this water?"

The main factors controlling water-quality interpretations for irrigation are: (1) nature of the analytical data, (2) chemical and physical characteristics of soils and substrata, (3) land drainage, (4) climate, (5) land use, (6) irrigation practices, and (7) ameliorative and control measures.

Analytical data generally are available but inadequate, and it usually is advisable to undertake special sampling programs. Quality and quantity must be correlated for adequate interpretations of the long-time effects of use for irrigation. The time and frequency of sampling are controlled by the nature of the supply. For flowing surface waters, the program will be governed by characteristics of flow and may vary between stations according to their importance. Whether samples are taken once a day, once a week, or once a month, the requirement and problem is that they represent the discharge at the time. Ground waters are not generally subject to appreciable variation in quality, but special problems arise, such as the reliability of samples from wells not being pumped and contamination of water in one aquifer by that from another at a higher level. Field and laboratory investigations, such as soil and land classification and the measurement of soil and crop responses to and influences on water of the anticipated quality, are essential. Existing drainage conditions must be evaluated and plans formulated for construction or rehabilitation of drainage systems. Adequate recognition of climatic conditions generally is lacking in interpreting water-quality data, and there is a paucity of criteria in this respect. The development of reasonably supportable salt-balance estimates requires correlating climate with soils, drainage, crops, irrigation practices, and water-quality data in each instance. Land use with respect to type and distribution of crops, and irrigation practice with respect to the time, depth, and frequency of application are an essential part of each evaluation. The data on crop tolerances and responses to waters of different quality are becoming more voluminous; but the culture-solution and plot-experimental work, from which the data derive, require careful interpretation.

A final important factor affecting water-quality interpretations is consideration of ameliorative and control measures, such as water treatment [McGEORGE and BREAZEALE, 1951], soil leaching [HUBERTY and PILLSBURY, 1950], soil amendments [BOTTINI and LISANTI, 1951; KELLEY, 1951; PUZENAT, 1950; McGEORGE and Others, 1952], soil ridging, and mixing of saline and nonsaline waters. Bacteriological control of irrigation water seldom is required [WRIGHT, 1950; DUNLOP and Others, 1951]. Data on the effect of industrial and municipal wastes are quite meager [IYER and Others, 1952].

Research and evaluation of experience with respect to the foregoing problems are essential. The greatest need is for regional inventories of irrigated lands correlating cropping experience, soils, and other physical factors with chemical water data. Clarification of most of the problems will evolve through orderly, planned research. There is current Federal support of research in the field of water treatment [see U. S. DEPT. OF THE INTERIOR, 1952], but the program has been too short-lived to produce any startling results. The permionic membrane and polysterene resin processes are two of the more promising currently being tested for field application to treatment of irrigation and domestic supplies in selected areas [MOORE, 1951; AULTMAN, 1952]. The practical feasibility of such water treatment in specific areas will depend upon such factors as water-quality requirements, initial and recurring costs, crop-production potentials, means for disposal of effluent or salts, and consumptive use of water.

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L. L. Doneen (Irrigation Department, University of California, Davis, California)--One of the outstanding problems in California is water penetration into soil. Studies have been undertaken to evaluate some of the factors affecting the infiltration rates of the soil. At the present time these investigations may be grouped into three subdivisions: (1) The destroying of structure by cultivation and tilling the soil by heavy farm equipment with a reduced infiltration from soil compaction. (2) Soils having naturally poor structure, usually heavy soils, or those laid down under water, and stratified soils. Many have extremely low infiltration rates. (3) The effect of salts in the irrigation water on soil and plant life.

The first two categories have been discussed in the following articles: Soil Conditions Affecting Infiltration of Water and Root Development of Crop Plants, by L. D. Doneen and D. W. Henderson [Proc. Amer. Soc. Sugar Beet Tech., pp. 214-223, 1952]; Compaction of Irrigated Soils by Tractors, by L. D. Doneen and D. W. Henderson [Agr. Eng., v. 34(2), pp. 94-95 and 102, Feb., 1953].

The third category is the one of principal interest for this report. The results of early investigations have been published as a Progress Report on the Water Penetration Studies in Kern County, and later in 1948 in the Proceedings of the Soil Science Society of America under the title of The Quality of Irrigation Water and Soil Permeability. The earlier reports were concerned with the addition of gypsum to irrigation water having a high percentage of sodium salts. Since then, standards for the quality of irrigation water have been investigated. In addition to the amount and kinds of salts in the irrigation water which influence water penetration, consideration is being given to the basic ionic effects. Some of these investigations are reported in the paper entitled Salination of Soil by Salts in the Irrigation Water, cited in the introduction to this report. This paper deals with only one of the many factors that should be taken into consideration in establishing standards for irrigation water. Some of the other investigations under way are: effect of kind and concentration of salts on soil structure and soil permeability, the toxic effects of individual ions and salts on plants, and the amount of leaching required to maintain a favorable salt balance in the soil solution. The work is being carried on in the laboratory, greenhouse, and under field conditions. The emphasis of this study is placed on well, drainage, and sewage waters, as these are the waters that fluctuate widely in salt concentration.

Otto M. Smith (Research Foundation, Oklahoma A. and M. College, Stillwater, Oklahoma)--The development of flural has been under study during the past several years. These studies are recorded in the article entitled Flural - A New Floculating-Fluoridating Agent [J. Amer. Water Works Assn., v. 44, pp. 71-75, Jan., 1952]. In addition, I am serving as a member of a committee of the American Water Works Association in revising the forthcoming standard methods of water analysis; and as part of that committee, I am in charge of the formulation of the procedure of the determination of selenium in water. Water samples containing selenium have been distributed to a number of laboratories, but the results of analyses made by these laboratories have not yet been assembled and put in shape for distribution.

W. W. Hastings (U. S. Geological Survey, Washington, D. C.)--The activities of the Geological Survey in the field of water chemistry as described in the report for 1951-1952 were continued during 1952-1953. The investigational programs involving the determination of the chemical characteristics of ground and surface waters throughout the United States were maintained at essentially the same level.

Several water-quality studies nearing completion are worthy of mention. Since 1948 the Survey has conducted studies of quality of water in Devils Lake in northeastern North Dakota. From 1867 to 1940 the lake level has dropped 37 ft; and with this decline, there has been a gradual deterioration of the water quality. Since 1940 a gradual rise in lake level has occurred, and improvement in quality of the lake water has been observed. In 1951 the lake had risen almost 15 ft since the low reading of 1940.

In Florida two noteworthy reports are nearing completion. Salt Water Intrusion in Florida, by A. P. Black, Eugene Brown, and J. M. Pearce, has been prepared and contains the history of the salt-water encroachment problem in Florida, with a discussion of the hydrologic principles involved. Cases of past and present salt-water encroachment are discussed, and an extensive bibliography is included. The second report deals with the Geochemistry of Ground Waters of Northeastern Florida and Southeastern Georgia, by Eugene Brown and A. P. Black. The report discusses the occurrence of natural ground waters, the solution and transposition of dissolved elements, and the cycles of these elements in nature. Also, the characteristics of the waters are considered in relation to the formation from which the waters are derived and their mineral content compared in regard to distance from recharge areas.

The Geological Survey has completed nine preliminary reports, covering the entire country, containing results of a study of the industrial utility of the larger public water supplies in the United States. Each supply is described, and a complete chemical analysis is included for the water furnished to consumers in the area. The data will be finally incorporated into two volumes containing information pertaining to public water supplies of more than 1200 cities in the United States which will be published in 1954 as a Geological Survey Water-Supply Paper.

U. S. Geological Survey (W. W. H.),
Washington 25, D. C.

(Communicated manuscript received November 17, 1953;
open for formal discussion until May 1, 1955.)

Transactions, American Geophysical Union   Volume 35, Number 6   December 1954

PROGRESS REPORT, SEISMOLOGICAL LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY, 1953

H. Benioff, B. Gutenberg, and C. F. Richter

(Contribution No. 661, Division of the Earth Sciences, California
Institute of Technology, Pasadena, California)

Station development

Changes in our seismograph installations during the past year are as follows: Barrett was equipped with three standard short-period and three standard long-period Benioff seismographs, one vertical-component short-period Benioff seismograph with low magnification, and one standard N-S torsion seismograph. Woody now has one standard short-period vertical Benioff seismograph and one standard E-W torsion seismograph. Isabella, located at $\Phi = 35° 38.6'$, $\lambda = 118° 28.6'$, $h = 760$ m, was established as a permanent station with one short-period Benioff vertical-component seismograph.

Kern County earthquakes (continued)

The preliminary curve of the elastic strain rebound characteristic included in our previous report based on a small number of aftershocks has been substantially modified during the past year as a result of additional data on over 200 shocks measured and located by Richter and assistants. Benioff finds that shocks originating southeast of the fault trace form a compressional release series of the form $a + b \log t$, whereas those on the northwest side form a shear series of the form $A + B[1 - \exp(-\alpha t^{0.5})]$. The characteristic to January 15, 1954, is shown in Figure 1. In the original theory of aftershock generation, Benioff assumed that aftershocks occur along the principal fault. The observed evidence from the Kern County sequence indicates that aftershocks occur on auxiliary faults within the original strain zone at least as much as on the principal break. In the opinion of Benioff and Gutenberg, some aftershocks may possibly originate as slips between

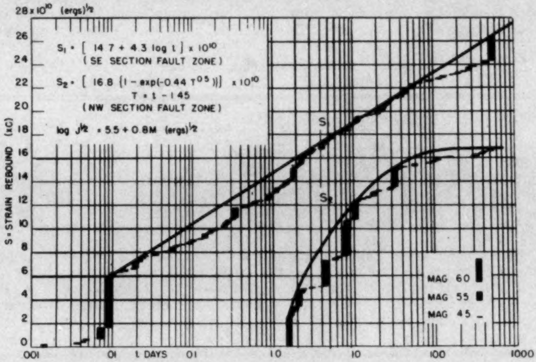

Fig. 1--Elastic-strain rebound characteristic of Kern County aftershock sequence, 1952-1953

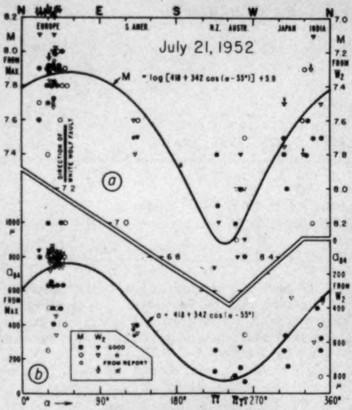

Fig. 2--(a) Calculated magnitude of main shock, July 21, 1952, and (b) calculated amplitudes at 84° epicentral distance; both are based on amplitudes of surface wave maxima (left scale) and of W2 maxima (scale at right) and are plotted as function of azimuth at the epicenter towards the station from north (0°) towards east (90°)

approximately horizontal zones in which the mechanical properties differ. The delay in onset of the shearing phase, also observed in other sequences, still remains unexplained.

The only records of the main shock of July 21 written at a nearby station which could be used for the calculation of the magnitude were those of the strong-motion seismographs at Pasadena. From these the magnitude was calculated M = 7.5. From records of 85 distant stations, Gutenberg finds M = 7.6. Magnitudes calculated from body waves are nearly independent of the azimuth of the station. However, surface waves recorded in Europe show maxima which at corresponding distances are about ten times as large as those recorded in Australia and New Zealand (Fig. 2). Aftershocks do not show this phenomenon. All indications are that in the principal shock faulting progressed northeastward with a speed not much smaller than that of the shear waves, thus concentrating the energy propagated in the direction of slip progression as compared to that propagated in the opposite direction, as anticipated theoretically by Benioff. The amplitudes of the surface waves at a given distance can be expressed rather closely by a sine function of the azimuth which indicates an average magnitude of 7.6 to 7.7. The azimuths of the maximum and minimum agree with the strike of the White Wolf fault within the limit of error, a few degrees.

For the larger aftershocks, magnitudes M have been determined by Gutenberg both from trace amplitudes written by torsion seismographs at the nearer stations and from ground amplitudes of distant stations. Representative results for the best recorded aftershocks are given in Table 1 (number of observations in parenthesis).

Table 1--Representative results for the best recorded aftershocks

Date	Time	Magnitude M based on		
		Nearby stations	Distant stations	
		Trace maxima	P and S	Surface waves
1952	h m			
July 23	00 39	6.1 (5)	6.2 (14)	6.0 (34)
July 25	19 10	5.8 (8)	5.7 (7)	5.8 (32)
July 29	07 04	6.2 (7)	6.0 (11)	6.1 (40)

The distribution of observed initial dilatations and compressions for the principal shock is shown in Figure 3. For the vicinity of the point of initial rupture (hypocenter), this distribution indicates a dip of the fault surface of about 63° southeastward. The direction of the first slip was upward in the upper (southeastern) block relative to the lower block. These data were not sufficient to compute the value of the horizontal component of slip.

Gutenberg has calculated the direction of slip using the polarization angle ϵ of the transverse waves ($\tan \epsilon = SH/SV$). He has calculated ϵ from the observed N-S and E-W components of S for any station with two horizontal components having about the same characteristics. On the other hand, ϵ can be found theoretically for a given difference δ between the azimuth of the ray toward the station and the strike of the fault, a given angle of incidence i of the ray, and a given angle of incidence ψ of the direction of slip. Equations developed by J. M. Nordquist for the relative amplitudes of SH and SV lead to

$$\cot \epsilon = (\cos i \cos \delta - \cot \psi \sin i)/\sin \delta$$

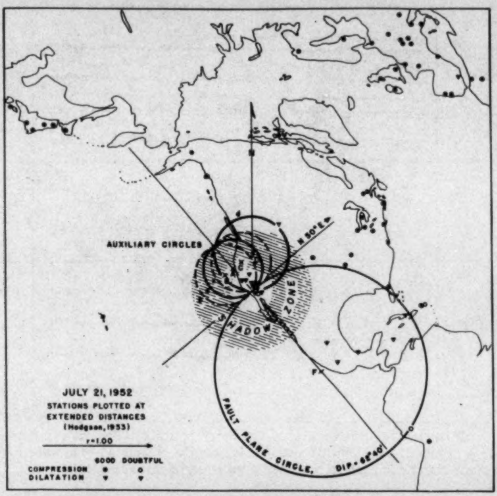

Fig. 3--Observed compressions and dilatations in the main earthquake of July 21, 1952; projection using 'extended distances' after Hodgson and Storey; shadow zone for longitudinal waves is indicated by shading

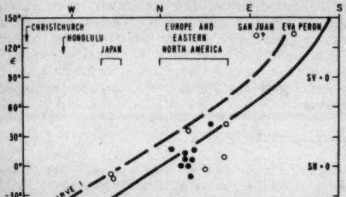

Fig. 4--Observed angle of polarization of S-waves as function of azimuth towards the station for the main earthquake, July 21, 1952; curve 1 is calculated for dip-slip along the surface of the White Wolf fault, curve 2 on the assumption that the slip was toward north in the upper block

The fact that $\delta = 0$, if $\epsilon = 0$, permits the rapid finding of the azimuth of fault slip, since it coincides with the azimuth in which SH is zero. Figure 4 indicates that in the main Kern County shock of July 21, 1952, the direction of slip was approximately towards the north in the upper block. The direction of slip makes an angle of about 70° with the horizontal.

A study of the seismograms provides additional evidence for the low-velocity layer at a depth of about 100 km. Records written at distances between about 4 and 16° show very small beginnings (see also Fig. 5). Starting at about 6° the first emergent P-motion is several seconds later than that given by the straight-line extrapolation of the travel-time curve for Pn, which was found by Gutenberg to be given by

$$t = [(5.1 \pm 0.9) + \Delta/(8.18 \pm 0.18)] \text{ km sec}$$

St. Amand has constructed charts on which the distribution of seismicity over the Kern County active area is shown by a smoothed system of contours. The release of strain in each small area is calculated as the sum of the quantities $J^{0.5}$ for units of 3.4 sq km. Figure 6a covers 1952 magnitude 4.0 and over, and Figure 6b refers to 1953 magnitude 3.0 and over. There were 18 aftershocks of magnitude 4.0 and over in 1953; the largest, on October 7, was 4.9. The corresponding total for shocks 3.0 to 3.9 was 198. On January 12, 1954, a shock of magnitude 5.9 occurred near 35.0° N, 119.0° W.

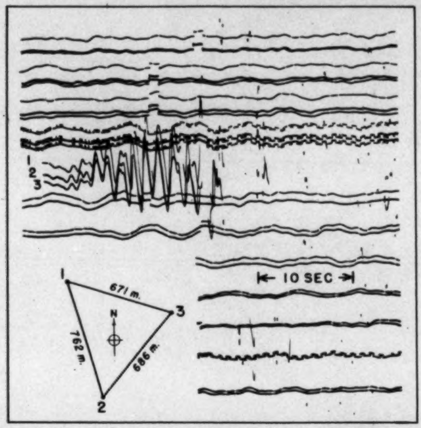

Fig. 5--P phases of earthquake of October 13, 1953, 08h 53m 45s ± near 30° N 114° W, recorded by Benioff vertical tripartite station at Palomar; epicentral distance about 4.5°; insert--relative location of instruments

Observations of blasts

Studies of blasts have been directed particularly to searching for waves reflected from the Mohorovicic discontinuity. G. Shor operated a multiple-trace prospecting-type seismograph in the vicinity of the quarry of the Monolith Portland Cement Company and near other large blasting operations. On these records and on seismograms written with short-period Benioff seismographs at short distances from other blasts, a definite wave appears with a travel time between 10 and 11 sec, which he identifies as a reflection from the Mohorovicic discontinuity at a depth of approximately 32 km. A similar earlier wave may be a reflection from a discontinuity some five km shallower. The results are correlated with those found previously from reflected and refracted waves in Southern California earthquake seismograms.

Instrument development

Quartz crystal clock--A new form of quartz crystal clock has been developed for use in place of marine-type chronometers. The timing element is a Bliley 100-kc standard oscillator. This unit has a low temperature-coefficient crystal maintained in a constant-temperature oven. The counter is made up of a series of Wang magnetic flip-flops known as Perma-Memory Multiple Scalers. With the 100-kc input to the counter, the output frequency is one per minute. Since the output from the counter consists of impulses of approximately ten microseconds duration, a pulse lengthening circuit has been provided for increasing the pulse duration to approximately 1.5 sec for operation of the relay which delivers current to the seismograph time-markers. In addition, the output impulse is connected to an IBM minute impulse clock for providing a visual indication of the time. The impulse clock is fitted with an hour cam for supplying contacts for the hour marks on the seismograms. The frequency stability of this crystal clock is approximately within one-tenth second per week. The original cost is considerably less than that of a good marine chronometer, and it is anticipated that the maintenance cost will also be less. Using a radio receiver tuned to WWV, the rate of this clock can be readily adjusted to within one part in 10^7 by observing beats between the 100th harmonic of the oscillator and the fundamental of WWV.

Fused-quartz strain meter--A fused-quartz earth-strain meter has been installed in an abandoned tunnel of the Los Angeles County Flood Control District situated in Dalton Canyon in the mountains north of Glendora. The fused-quartz indicator tube is 25 m long. Secular strains are measured with a filar microscope reading to 0.001 mm, corresponding to an earth strain of 4×10^{-8}.

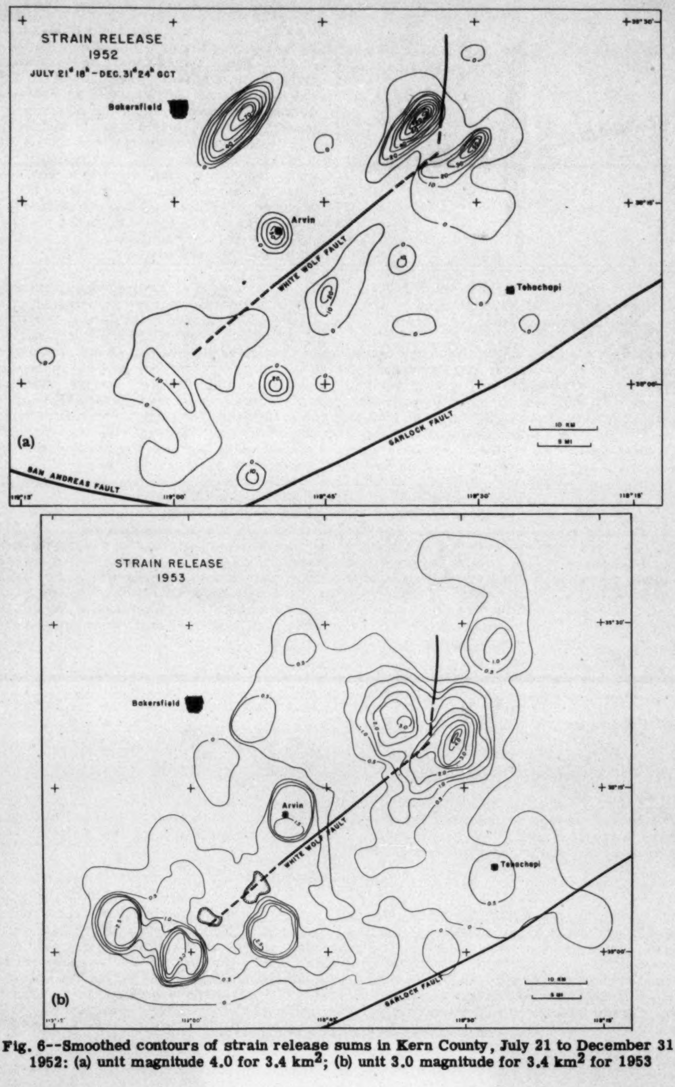
STRAIN RELEASE
1952
JULY 21d 18h - DEC. 31d 24h GCT
Bakersfield
Arvin
WHITE WOLF FAULT
Tehachapi
GARLOCK FAULT
SAN ANDREAS FAULT
10 KM
5 MI
(a)
119°15'
119°00'
118°45'
118°30'
118°15'
35°30'
35°15'
35°00'
STRAIN RELEASE
1953
Bakersfield
Arvin
WHITE WOLF FAULT
Tehachapi
GARLOCK FAULT
10 KM
5 MI
(b)

Fig. 6--Smoothed contours of strain release sums in Kern County, July 21 to December 31, 1952: (a) unit magnitude 4.0 for 3.4 km²; (b) unit 3.0 magnitude for 3.4 km² for 1953

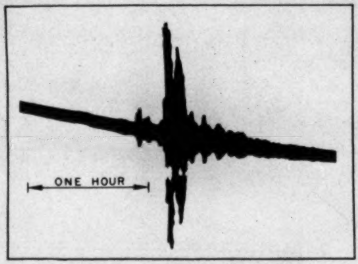

Fig. 7--Record of Japanese earthquake, November 25, 1953, written by quartz strain meter at Dalton, California

Preliminary photographic recording of dynamic strains has been started using a double bowstring optical mirror device with a magnification of 12,000. The resulting recording has a sensitivity of one mm per 3×10^{-9} strain. With this magnification the Earth tides are clearly recorded. The present recording drum speed is one cm per hour. It is planned to include two additional recorders operating at a faster and a slower rate. These will be actuated by a capacity transducer operating with a constant-frequency carrier oscillator as described in our previous reports. A copy of a recording of an earthquake is shown in Figure 7. The instrument was constructed with funds provided by the Geological Society of America.

Long-period vertical-component seismometer--A vertical-component seismometer for long-period waves is being developed. The instrument has a period of ten seconds and is overdamped electromagnetically approximately ten times the critical value. Output is derived from a capacity transducer of the type described in our previous report except that the oscillator operates at 100 kc and is driven by transistors. The pendulum has two alloy springs. One is mounted vertically and supports the pendulum mass. The other is mounted horizontally and provides a negative restoring force which increases the period from one second with vertical spring only to ten seconds with both springs acting. The transducer output is proportional to the pendulum displacement rather than the velocity as in electromagnetic instruments; and it is expected, therefore, to provide a better response for waves longer than one or two minutes.

Project sponsored by the Geophysics Research Division of the Air Force Cambridge Research Center

The vertical-component tripartite seismograph mentioned in our previous report has been completed for operation with temporary galvanometers. In addition to the recording of microseisms, the instrument has recorded a number of local and distant earthquakes (Fig. 5). Work is progressing on the completion of an additional triple recorder for operation of the two strain seismometers on separate channels and an additional channel for the combination or sum of the two components. The two moving coil electromagnetic horizontal-component instruments are in operation with the vectorial recorder.

Travel times of longitudinal waves from surface foci in the Pacific Ocean

Residuals for 33 observed P-waves from Pacific surface sources relative to the Jeffreys-Bullen tables for surface foci were found as follows:

Distance, degrees	35 - 40	50 - 65	68 - 79	80 - 91
Residuals, seconds	-1.7 ± 0.6	-3.9 ± 0.4	-1.3 ± 0.6	-1.1 ± 0.7

Of these residuals, probably about -2 sec are a consequence of the difference in the velocities between continents and Pacific bottom. There were also available a few observations of certain waves through the core giving relatively small residuals. The residuals for P show the same trend as those found from the shock of July 21, 1952.

Long-period waves

In our previous report, mention was made of waves with periods up to 7.9 min recorded on the seismogram of the Kamchatka earthquake of November 4, 1952, written with the three-minute-period low-magnification electromagnetic strain seismograph. On the same seismogram the mean position of the recording line appeared to be disturbed during the time these waves were recorded. Since the recording line was undisturbed on the day preceding the shock as well as the following day, it seemed desirable to investigate the possibility that this disturbance might be an ultra-long-period strain associated with the earthquake. Accordingly, a copy of the seismogram was drafted by Gilman in which the ratio amplitude/time was increased 22 fold. This had the effect of reducing the recording rate 22 fold. The drafting was carried out using measured positions of the line displacements at minute intervals. A copy of the drafted seismogram is shown in Figure 8. Beginning approximately 3.5 hours after the time of origin there appears an oscillation or wave train of four cycles with a period of 57 min. Approximately 30 min after origin time a fairly sudden dilatation occurred followed by a movement of several hours' duration. In a later portion of the seismogram, not shown in the figure, another wave train or oscillation began at approximately 7.7 hours after the origin time. This movement has a period of approximately 100 min.

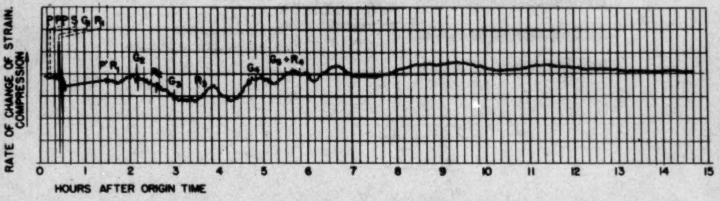

Fig. 8--Seismogram of Kamchatka earthquake, November 4, 1952, recorded by Benioff strain seismograph at Pasadena, drafted with 22 fold reduced recording rate

The origin of these ultra-long-period oscillations is not clear. The very long-period dilatation beginning at 30 min may represent a readjustment of the world crustal strain pattern in response to the release of a compressional strain on the Kamchatka fault. The 57-min and 100-min oscillations may represent free vibrations of the Earth as a whole or of the mantle as a whole. A possible mode for the 57-min vibration is one in which the Earth takes on the forms of a prolate and oblate ellipsoid alternately. In Figure 8 the straight portion of the seismogram between R_1 and $P'R_1$ represents the mean line position for a long train of Rayleigh waves on the original seismogram with periods too short (approximately 20 sec) to be resolved in the drafted copy.

Waveform of the seismic source

Observations of nearly identical recorded wave forms in different earthquakes from the same or nearly the same focus indicate that in general earthquakes represent wave sources of simple form. The complex wave form of most seismograms is thus primarily a result of complexity of path. Under special conditions of observation, the approximate form of the original impulse can be determined. A number of such wave forms with breadths varying from a fraction of one second to 70 sec have been studied from the seismograms of the laboratory. In general, the recorded pulse corresponds in shape with the displacement, velocity, or acceleration forms of Ricker's wavelets. It appears, therefore, that the source has the approximate form of a step function, a spike, or a spike doublet (Fig. 9).

Investigation of waves through the core

The phase SKP (PKS) was investigated by R. D. Forester (Ph.D. thesis, Division of the Geological Sciences). Most records used belong to shocks originating at depths between 15 and 100 km. They frequently show multiple SKP phases, sometimes extending for more than one minute. The main focal point of the wave is found at an epicentral distance of about 131.5° for waves with periods of five to ten seconds. Forester considers multiple reflections and refractions as the most plausible reason for the multiplicity.

The calculated energy of SKP agrees with the observations for the vertical component but exceeds the observed values for the horizontal component. Observations of SKP through the inner core give additional support for the hypothesis of a relatively large but continuous increase in wave velocity at the transition from the outer to the inner core.

Postglacial uplift

New data concerning crustal uplift in Norway, the Great Lakes area, and Churchill, Hudson Bay, were studied in combination with earlier data. It is concluded that the contemporary uplift in Fennoscandia and in northern North America is mainly a recovery with a time constant of approximately 8000 years following the melting of the ice after the Ice Age, and that, contrary to

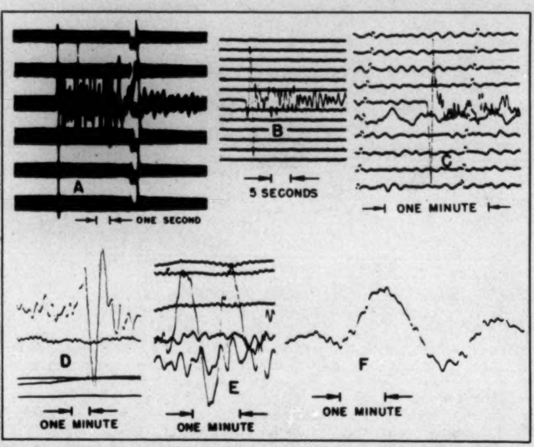

Fig. 9--Examples of wave forms in Pasadena seismograms: (a) small aftershock of Kern County earthquake recorded on Benioff vertical-component portable seismograph located near epicenter of principal shock; (b) intermediate depth New Guinea earthquake of February 17, 1951, recorded with Benioff vertical-component seismograph $T_g = 0.20$ sec; (c) seismogram of South American intermediate depth earthquake of February 29, 1944, recorded with Benioff vertical-component seismograph $T_g = 115$ sec; (d) electromagnetic strain seismogram of G_1 wave of Kamchatka earthquake of November 4, 1952, $T_g = 180$ sec; (e) electromagnetic strain recording $T_g = 70$ sec of S wave of shallow South American earthquake of November 1, 1947; (f) G_2 wave from same record as D

opinions expressed repeatedly in recent years, tectonic processes play only a minor role in this movement.

Routine observation of local and distant earthquakes

During 1953, one great distant earthquake was recorded on November 25, magnitude 8.0, off Japan. In Southern California only one shock exceeded magnitude 5; this occurred on June 14, 04h 17m 28s GCT, at 32° 50′ N, 115° 40′ W, near Imperial; magnitude 5.5.

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A METHOD FOR ESTIMATING THE HEIGHT OF CIRROSTRATUS CLOUDS

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Abstract--Difficulties in estimating the height of cirrus clouds and the rather frequent gross error in the reported estimates have been pointed out from time to time. Until the recent development of operational interest in such high levels, this problem had not been given much attention. An approach to the problem was suggested by the oft-reported observation of pilots that when cirrostratus is present, condensation trails usually form when the aircraft nears the cirrus level. This implied that the contrail-forecasting chart used by Air Weather Service might also be used to estimate the height of an existing cirrus layer.

Introduction--The forecast height of contrail formation is obtained by locating the intersection of the representative raob sounding with the proper contrail-forecasting curve (Fig. 1) [APPLEMAN, 1953]. In order to select the curve to be used, it is necessary to know, by measure or by estimate, the relative humidity. Unfortunately, present-day radiosondes are incapable of accurately measuring relative humidity at the low temperatures where cirrus occurs. The very fact that cirrus is present, however, indicates that the relative humidity must lie between water and ice saturation. At a temperature of -40° C, ice saturation is equivalent to a relative humidity of 68 pct with respect to water. Consequently it was decided to test both the 90 and 100 pct contrail curves.

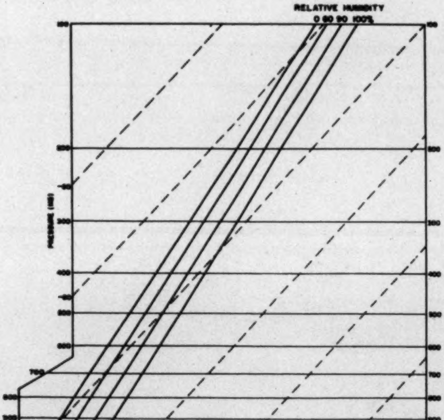

Fig. 1--A graph of the relative humidity required for contrail formation as a function of the pressure and temperature of the environment

Procedure--A total of 45 cirrus height observations were available from RB-47 flights made between June and December, 1952. Only those cases were selected in which the aircraft actually penetrated the cloud base or approached sufficiently close so that the estimated heights could be considered nearly as accurate as actual measurements. These RB-47 data are considered as giving the 'true' heights of the cirrus bases.

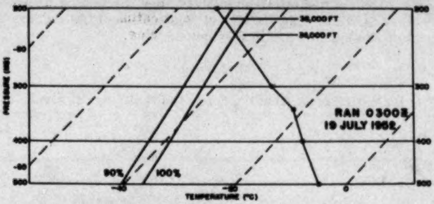

Fig. 2--Example of use of 90 and 100 pct critical humidity contrail curves in estimating height of cirrus over Rantoul on July 19, 1952

For each of the true heights, the estimated heights were obtained by locating the intersections of the 90 and 100 pct contrail curves with the raob sounding nearest in time and space to the cirrus report (Fig. 2). Some of the raobs, of course, were as much as six hours and several hundred miles from the location of the cirrus.

Another set of estimated heights was obtained from the hourly sequences from the Air Weather Service station nearest in time and space to each cirrus report. Due to their greater density and frequency, the surface observations are much closer in space and time to the aircraft reports than are the upper-air soundings. In ten cases, mainly because of the intervening lower cloud layers, the surface observer failed to report the cirrus observed by the aircraft. This reduced the number of usable reports from 45 to 35.

Results--Table 1 shows the comparative accuracies of the estimates made by the observer and by use of the 90 and 100 pct contrail curves.

Table 1--Comparative accuracies of methods for estimating the height of cirrostratus clouds

Number of estimates	Surface observer	90 pct curve	100 pct curve
Total	35	35	35
Within ±3000 ft	3	25	27
±3500 to ±5000 ft	4	8	6
Over ±5000 ft	28	2	2
Average error, ft	9600	2400	2500
Algebraic error, ft	-9600	+700	-1160

In every case the surface observer underestimated the height of the cirrus layer, usually by more than 5000 ft. This was due to the observer's generally reporting some fixed value such as 20,000 or 25,000 ft, whereas the cirrus usually occurred between 30,000 and 40,000 ft. The average error of the surface observer was 9600 ft. The estimates made by using the contrail curves were sometimes too high and sometimes too low. The 90 pct curve gave a mean error of 2400 ft, averaging 700 ft too high. The 100 pct curve gave a mean error of 2500 ft, averaging 1160 ft too low.

Conclusions--This study is primarily concerned with the broad areas of cirrostratus rather than those produced locally by thunderstorms. As yet, accurate data in sufficient amount are not available to draw firm conclusions as to the accuracy of the method presented here. Further testing is underway. However, since the estimates made by the surface observer averaged so much poorer in this test, it seems probable that the use of the 90 pct contrail forecasting curve may be of real value in estimating the heights of cirrostratus layers.

In addition to its greater accuracy, another advantage of operational importance is gained from the use of the contrail curves. This method can be used to estimate the height of a cirrostratus layer concealed by a lower overcast. The existence of such a cirrus layer cannot be determined by this method, since the use of the 90 pct curve assumes cirrus is present. But the curve will indicate the height at which cirrus would be found in case it should exist.

Acknowledgments--The method used was evolved in a discussion between the author and R. Lame of the Air Weather Service. The statistical verification of the method was accomplished by Thomas H. Simmonds of Headquarters, Air Weather Service.

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LETTER TO THE EDITOR

AIDS FOR LOCATING TRANSLATIONS

The bibliography on snow, ice, and frozen ground being prepared at the Library of Congress for the Snow, Ice, and Permafrost Research Establishment, Corps of Engineers, was described in an earlier Letter to the Editor (October, 1953). As part of the bibliography program, an information file is maintained on translations of foreign references appearing in the bibliography. Duplication of translations is most undesirable and, in many cases, inexcusable since a survey of a large number of existing translations can now be easily accomplished. It is the purpose here to briefly review the more important aids for locating technical translations which are available to the general public.

Two groups in this country are engaged in collecting English translations of foreign scientific writings for the purpose of making these translations generally available. The Scientific Translations Center has been established in the Science Division of the Library of Congress, Washington, D. C., under the joint sponsorship of the National Science Foundation and the Atomic Energy Commission. This group issues a monthly publication under the title Bibliography of Translations from Russian Scientific and Technical Literature announcing translations which have been deposited with or loaned to the Center by government agencies, scientific societies, universities, and other organizations. Notices of translations offered for sale by commercial and other translation services are included when available. To date, over 2400 translations from Russian have been listed. The translations are listed alphabetically by author under broad subject headings and include appropriate bibliographic data. This publication is available at a yearly cost of $3.00. Positive microfilm copies of the translations are available at a cost of $1.00 for one to 50 pages, $1.50 for 51 to 100 pages, and $0.50 for each additional 50 pages or fraction thereof. The charge for enlargement prints is $1.25 for one to ten pages, $1.75 for 11 to 15 pages, and $0.10 for each additional page.

Translations from all languages except Russian are handled in a similar manner by the Special Libraries Translations Pool at the John Crerar Library, Chicago, Illinois. A list of the 1300 translations forming the nucleus of the Pool was published in October, 1953. This list, arranged alphabetically by author, is available at a cost of $0.30. A supplement listing 700 additional translations received since October, 1953, is now available at a cost of $1.00. Photoprint or microfilm copies of the translations are available at the rate of $1.40 for ten pages or less on photoprint, or 50 pages or less on microfilm, plus a service charge of $1.00 for each translation.

Similar information is available from agencies outside this country. The National Research Council of Canada at Ottawa published a List of Technical Translations in August, 1953, which contains approximately 400 translations. The list is presented in the numerical order of completion and includes an author index. Supplements to this list will be published from time to time. Additional information on translations by the Research Council can be obtained from their Division of Information Services.

Perhaps the most noteworthy group outside of the United States concerned with translations is an organization in England, sponsored by the British Commonwealth Scientific Office, known as the Association of Special Libraries and Information Bureaux (ASLIB). Representatives in commonwealth countries forward information on translations to this group. At present, approximately 12,000 translations are listed from all languages, mostly from journals. No lists are published, but journal and author files on these translations are maintained. On request, ASLIB will check the files for desired references and, if found, can arrange for loan, purchase, or photocopy. No charge is made for the file search. Requests should be sent to ASLIB, 4 Palace Gate, London W. 8, England.

Technical Information Division,
Library of Congress,
Washington, D. C.

John Sherrod, Jr.

REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

COLMAN, E. A., Vegetation and Watershed Management - An Appraisal of Vegetation Management in Relation to Water Supply, Flood Control, and Soil Erosion, Ronald Press Co., New York, xv + 403 pp., 1953, $7.00 (sponsored by the Conservation Foundation).

The first of its three parts is a brief presentation of general facts and problems relating to water yield and control. The second part, principles of water-yield control, discusses hydrologic processes, mostly with respect to the roles of soil and vegetation. The third part, vegetation and water-yield control, is organized largely on a geographical problem-area basis and repeats much of what is in Part II.

The introductory chapter of Part III contains a significant contribution in the form of a map showing regions of different kinds of natural vegetation and uses of cultivated land in the United States. The chapter on fire does not condemn deliberate burning of vegetation as universally as some authorities do. One of the chapters discusses techniques of research for evaluation of land-use practices. Each chapter of Part III concludes with a summary.

Colman is objective on controversial issues. While he qualifies many of his statements, opportunities are unusually numerous for biased or careless readers to quote misleading statements out of context. The two main faults of the book are the extensive repetition and the lack of quantitative treatment of processes that have been the subject of investigations by hydrologists and conservationists at a cost of many millions of dollars during the past twenty years. The vogue of many foresters and soils men is followed in referring to natural water as a product of the land.

The book has many virtues. Perhaps its greatest virtue is the emphasis on recognition of the entire problem. This is in welcome contrast to recent pressures for one method or objective, the singling out of one part of the problem for dramatic attention while ignoring essentially related aspects. The book is detailed, comprehensive, and authoritative. It ranks as a text in hydrologic aspects of soil and plant management, yet is written in a modest and easy style that will bring to many non-technical readers a good understanding of processes and practices for controlling soil and water movement.

The quantitative data given are almost entirely in comparisons of runoff and soil loss from plots under different kinds of treatment. With plots there is prevention of sedimentation, runoff, and subsurface flow from areas that would be tributary to any but ridge sites under natural conditions. Colman cites the dangers of extrapolation and generalization without control or measurement of the pertinent variables in the entire soil-vegetation-water complex and emphasizes the need to consider all the pertinent facts in appraising the problem; but he cites so many plot results that his cautions and qualifications may not properly be kept in mind.

The final chapter recommends investigations of specific problems, and concludes with a plea to apply research findings in operational programs. The book is well documented with more than 300 citations, mostly of recent American literature.

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NOTES AND PERSONALIA

NOTES

Corrigendum--In the issue of October, 1954, in the paper by Don Kirkham, page 777, an error occurs in the right-hand member of Eq. (8), which should read as follows:

$$K_1 \left[\partial\phi_1'/\partial y\right]_{y=-(h-d)} = K_2 \left[\partial\phi_2'/\partial y\right]_{y=-(h-d)} \quad \ldots\ldots\ldots\ldots\ldots \quad (8)$$

Graduate Assistantships in Meteorology and Climatology at Florida State University--The Florida State University has announced the availability of graduate assistantships, carrying stipends of $1620 and $1920 per year plus waiver of out-of-state tuition fees, for graduate study in meteorology and climatology. Appointments will be made primarily in connection with research projects being conducted for the Office of Naval Research and the Geophysics Research Directorate, Air Force Cambridge Research Center. The student is permitted to carry as many as ten semester hours of course work. Minimum requirement for consideration is a bachelor's degree from an accredited institution with two years of university mathematics and one year of university physics. Applications for assistantships should be filed before May 1, 1955. For application forms and further information, write to Werner A. Baum, Head, Department of Meteorology, Florida State University, Tallahassee, Florida.

Eighteenth International Geographical Congress--This Congress is scheduled to be held in Rio de Janeiro, August 9-18, 1956. The Executive Secretary of the Congress, Hilgard O'Reilly Sternberg, requests that those geographers not included in the World Directory of Geographers published in 1952 by the International Geographical Union send their names and addresses to him. He also desires new addresses for those listed who have moved. His address is Av. Presidente Antonio Carlos 40, 9º andar, Rio de Janeiro, Brazil.

New geochemical laboratory at Columbia University--A new geochemical laboratory, located at the Lamont Geological Observatory of Columbia University at Palisades, New York, has just been completed. Research in progress includes age determinations by various isotopic and other methods, measurement of natural radioactivity of crustal materials and the atmosphere, and various geochemical investigations relating, for example, to petroleum and sulphur. The laboratory is under the direct supervision of J. Laurence Kulp.

Symposium on Typhoons--An international symposium on typhoons was held in Tokyo, November 9-12, 1954, under the sponsorship of UNESCO. Among those attending from the United States were R. H. Simpson and Jerome Namias of the U. S. Weather Bureau, James H. Hughes of the Office of Naval Research, Herbert Riehl of the University of Chicago, and Leon Sherman of Florida State University.

Annual meeting of the Eastern Snow Conference--The Eastern Snow Conference will hold its annual meeting in Burlington, Vermont, February 10-11, 1955. Interested persons should get into touch with the Secretary, Dean B. Bogart, U. S. Geological Survey, P. O. Box 948, Albany 1, New York.

International arid lands meeting--Under the joint sponsorship of UNESCO and the American Association for the Advancement of Science, this meeting will be held in New Mexico, April 26 to May 4, 1955. A symposium is planned to be held in Albuquerque, April 26-29, field trips on April 30 and May 1, and a closing conference in Socorro, May 2-4. Gilbert F. White, President of Haverford College, Haverford, Pennsylvania, is Chairman of the Planning Committee.

Grants of the National Science Foundation--The National Science Foundation has announced the awarding of 216 grants in various fields of science, including 14 in the Earth sciences, and several in chemistry, physics, engineering, and other fields that bear heavily on the Earth sciences. Details may be secured from Press and Radio Release 106 of the Foundation.

Establishment of the European Center for Nuclear Research (CERN)--A convention drawn up under the auspices of UNESCO for the establishment of a European Center for Nuclear Research has recently been ratified by France and Germany. Previously, Great Britain, Switzerland, Denmark, Greece, Sweden, Belgium, and The Netherlands had ratified the convention. The convention was to go into effect upon ratification insuring 75 pct of the total contemplated budget. As the two latest ratifications assure this support, steps to bring CERN into existence are now under way, this being cited by the French as "the first collective research organization in the history of the world." The laboratory is governed by a council having representatives from each adhering nation, and Felix Bloch has been appointed Director. The site of the laboratory is about six miles southwest of Geneva, and lies in Switzerland near the French border. The laboratory is now under construction and the foundation for a 600-Mev synchrotron will soon be complete. Plans for a 25-Bev alternating gradient proton synchrotron are well advanced.

New seismic stations of the West Rift Valley, Africa--The Institute for Scientific Research in Central Africa is establishing three new stations at Lwiro (2°15′ S, 28°48′ E), Uvira (3°24.5′ S, 29°08′ E), and Astrida (2°36′ S, 29°44′ E). Each station will be equipped with a Benioff variable reluctance vertical seismograph and two Wood-Anderson horizontal torsion seismographs.

Serious drought in progress--The U. S. Geological Survey has announced that a major drought is now in progress in the United States comparable to that of the early 1930's, extending through the southern and central states and into the East. The heavy rains accompanying Hurricanes Edna and Hazel mitigated the situation somewhat in many eastern areas. Ground-water and reservoir levels and stream flow are at or near record low levels throughout the southern two-thirds of the nation.

New Quartermaster Research and Development Center--The Quartermaster Corps of the U. S. Army dedicated its new Research and Development Center at Natick, Massachusetts, on October 14, 1954. The Center consists of a group of modern buildings on a 100-acre site on the shore of Lake Cochituate to house the various and diverse research activities. Milton Greenberg represented the AGU at the dedication ceremonies.

Establishment of Astronautical Society--A new scientific society, called the American Astronautical Society, has been established with headquarters at 516 Fifth Avenue, New York 36, New York. Its purpose is to "disseminate and support creditable proposals for the conquest of space, . . ., and to enlarge upon the consequences and benefits of man's greatest advanture." Volume 1, Number 1 of the new journal, Astronautics, contains five papers, plus book reviews, abstracts, and other material. The new society is a member of the International Astronautical Federation.

Oceanographic Institute planned for Venezuela--The Venezuelan Association for the Advancement of Science has announced that Raf Werner Ladiges, formerly connected with the Oceanographic Institute at Hamburg, has been selected to go to Venezuela to aid in the establishment of and to assume the directorship of a similar institute there. It is anticipated that the new Institute will be located at Higuerote, just east of Caracas, or at Cumaná, the capital of Sucre. Later word indicates that a marine biological station will be established at Cumaná and an aquarium will be established at Higuerote.

Expenditures for research and development--The National Science Foundation has reported that Federal agencies have obligated a total of about $1.99 billion for research and development during fiscal year 1955. This is about ten per cent less than that obligated in fiscal year 1954. It is estimated that in excess of $1.0 billion is expended annually by industry in support of research and development activities in industrial laboratories and that the total national annual expenditure is approximately $3.5 billion.

PERSONALIA

Robert Balk of the New Mexico Bureau of Mines and Mineral Resources is on leave from his duties there and is serving as Visiting Professor of Structural Geology at California Institute of Technology.

Michael Ference, Jr., has resigned his position as Chief Scientist of the Evans Signal Laboratory and taken up duties as Chief Scientist of the Scientific Laboratory of the Ford Motor Co. with headquarters in Dearborn, Michigan. On October 1 he was cited for "outstanding performance of duty" and given the Army's Exceptional Civilian Service award for his work at Evans Signal Laboratory.

Vaughn E. Hansen is on leave from his work as Research Associate Professor of Irrigation Engineering at Utah State College and is serving as Assistant Chief Engineer for the Hydrotechnic Corp. on water resources studies in Angola.

George H. Hickox, on leave from his duties as Associate Director, Engineering Experiment Station at the University of Tennessee, is serving as Program Director for Engineering Sciences, National Science Foundation.

Philip B. King, on leave from the U. S. Geological Survey, is serving as Visiting Professor of Geology at the University of California at Los Angeles.

Carroll F. Merriam of the Pennsylvania Water and Power Co. in Baltimore plans to retire from his work early next year, and he will take up residence in his native New England, probably in Maine.

Brian O'Brien, Vice President in Charge of Research of the American Optical Co. and Chairman of the Division of Physical Sciences of the National Research Council, has resigned as Director of the Institute of Optics of the University of Rochester, from which position he has been on leave. He will continue as a member of the Advisory Committee of the Institute.

Carl Rohwer, Senior Irrigation Engineer with the Division of Irrigation of the Soil Conservation Service, in charge of the work of the Division in cooperation with Colorado A and M College, has retired after 40 years of service with the Federal Government.

William W. Rubey is on leave from his duties as Research Geologist with the U. S. Geological Survey and is serving as Visiting Professor in the Institute of Geophysics of the University of California at Los Angeles. He has, until recently, served also as the Chairman of the National Research Council.

Thorndike Saville, Dean of the College of Engineering of New York University, has been named President General of the Fifth International Congress on Coastal Engineering.

John S. Shelton is on sabbatical leave from his professorship in the Geology Department of Pomona College and is devoting his time to a study of the terraces of the Western Mediterranean Sea. He plans also to do some work at the Eidgenosse Technische Hochschule in Zurich.

Thomas G. Andrews, Professor of Geology, University of Alabama, died July 23, 1954, at the age of 51. He was born at Jackson, Tennessee. He took his baccalaureate degree from Vanderbilt in 1925, his master's degree from the same school in 1927, and his doctorate from the University of Minnesota in 1932. He began his teaching career at Vanderbilt in 1926 and held an assistantship at the University of Minnesota while studying for his doctorate. In 1932, he began his work at the University of Alabama, devoting his summers and other periods to work with the U. S. Geological Survey. He became Head of the Department of Geology at Alabama in 1940. He made a specialty of the study of the occurrence and properties of iron ores. He had been a member of AGU since 1942.

Samuel Whittemore Boggs, Special Adviser on Geography in the Department of State, died September 14, 1954, at the age of 65. He was born at Coolidge, Kansas. He took his baccalaureate degree from Berea College in 1909, took some advanced studies at Yale in 1912-1913, and his master's degree from Columbia in 1924. He received an honorary doctorate from Berea College in 1949. His experience was wide and varied, and in 1924 he became the Geographer of the Department of State, continuing in this work until his death. During this interval, he undertook numerous important assignments with the U. S. Geographic Board, the Federal Board of Surveys and Maps, and other such bodies, both national and international. He had been a member of AGU since 1943.

John P. Buwalda, Professor of Geology at California Institute of Technology, died on August 19, 1954, at the age of 67 while on a field trip. He was born at Zeeland, Michigan, and took his baccalaureate degree from the University of California in 1912, and his doctorate in 1915. During the first years of his professional career until 1926, he was connected with the University of California, starting as an instructor and becoming professor in 1925. In 1926 he took up his duties with the California Institute of Technology, becoming Chairman of the Division of Geological Sciences, from the chairmanship of which he retired in 1947. His specialties were tectonophysics and structural geology. He became a member of AGU in 1934.

Charles Charlier, Secretary of the Belgian Organizing Committee for the Ninth General Assembly of the IUGG, associated with the Seismological Service of the Royal Observatory of Belgium, died on November 21, 1953, at the age of 56.

Austin Hobart Clark, Curator of the U. S. National Museum, retired as an honorary Associate, died October 28, 1954, at the age of 73. He was born at Wellesley, Massachusetts, and took his baccalaureate degree from Harvard in 1903. For over two years, he did research work on birds in the West Indies and then served as Naturalist on the expeditions of the U.S.S. Albatross of the Bureau of Fisheries. In 1908, he began his work with the Smithsonian Institution and became Curator of the Division of Echinoderms in 1920. At the end of 1950, he retired as Curator but continued his active work with the Museum as Associate. During his long career, he undertook numerous special assignments, such as membership on the Board of Advisers to the Virginia Fisheries Laboratory, and with various organizations to which he belonged. He became a member of AGU in 1932.

Oswald H. Dodkin, Advance Planning Engineer for Cia Brasileira Administradora de Servicos Técnicos, Ltda., in São Paulo, Brazil, died September 7, 1953, at the age of 52. He was born at Foxborough, Massachusetts, and took his baccalaureate degree from Worcester Polytechnic Institute in 1923. After three years of consulting engineering work, he went to Brazil as a testing engineer with the São Paulo Tramway, Light and Power Co. serving them as Chief Engineer from 1940 to 1948, at which time he undertook duties as Planning Engineer. He had been a member of AGU since 1949.

Wladyslaw Gorczynski, Professor of Meteorology and Climatology at Copernicus University, Torun, Poland, died June 25, 1953, at the age of 74.

Clarence E. Gordon, Professor Emeritus of Geology and Mineralogy, University of Massachusetts, died August 28, 1951, at his home in Amherst after a lingering illness. He was born in Clinton, Massachusetts, in 1876, and took his baccalaureate degree from Massachusetts Agriculture College (now the University of Massachusetts) in 1904, his master's degree at Columbia University in 1905, and his degree of Doctor of Philosophy from Columbia in 1911. He entered his career as a teacher in 1906, continuing at the same school through his career until his retirement in 1946, but serving various colleges and other organizations in diverse capacities for short periods. He became a member of AGU in 1934.

Edward Hyatt, State Engineer of California, retired, died June 17, 1954, at the age of 65. He was born in San Jacinto, California, in 1888 and got his baccalaureate degree from Stanford University in 1912. During his student years, he entered the service of the U. S. Geological Survey. Upon his graduation, he became an engineer for the San Joaquin Light and Power Corp. In 1914 he entered the service of the State of California, first with the Highway Commission and later with the Water Commission. He became State Engineer in 1927 and continued in this office until his retirement in 1950. He had been a member of AGU since 1947.

Florence Robertson, Professor of Geophysics, Saint Louis University, died November 18, 1954, at the age of 45. She was born in Paris, Texas, took her baccalaureate degree from Texas Technological College in 1935 and her master's degree from the same school in 1936. She took her doctorate from Saint Louis University in 1945. She took some advanced work at the University of Colorado in 1937. Since 1939, she had been connected with the Institute of Technology at Saint Louis University and received the full rank of Professor for her outstanding scientific and teaching work in geophysics, most notably, in seismology. She served as Secretary of the Section of Seismology from 1947 to 1950, as well as on various committees. She had been a member of AGU since 1939.

Frederick LeVerne Serviss, Professor of Geology at Purdue University, died July 22, 1954, at the age of 58. He was born at Telluride, Colorado, and took his baccalaureate degree from Coloradc School of Mines in 1920 and his master's degree from the same school in 1922. He taught at Catholic University from 1923-1929, taking advanced work at the same time at George Washington University. He began his work at Purdue University in 1929 and became Professor of Geology in 1935. He devoted various periods to field and consulting work. He had been a member of AGU since 1938.

Louis J. Wilbert, Jr., Assistant Professor of Geology at Louisiana State University, was killed in an automobile accident on March 17, 1953. He was born at Plaquemine, Louisiana, in 1919. He received his baccalaureate degree from Louisiana State University in 1940 and his master's degree from the same school in 1942. He took his doctorate from the University of Kansas in 1951. Following the war he was an instructor at Louisiana State University. He became a member of AGU in 1952.

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UNION, SECTION, AND COMMITTEE ACTIVITIES

INFORMAL REPORT ON THE TENTH GENERAL ASSEMBLY OF THE INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS HELD IN ROME, ITALY, SEPTEMBER 14-25, 1954

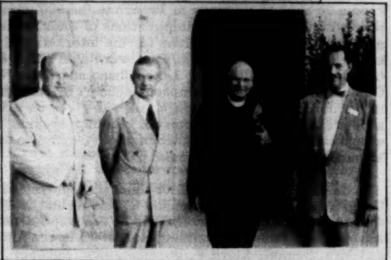
The Tenth General Assembly of the International Union of Geodesy and Geophysics was held in the Palazzo dei Congressi of the EUR (the International Exposition Grounds) about five miles south of Rome just east of the Tiber, from September 14 to 25, 1954. Registration began on September 13. The Commission on Finances met on September 11 and 13, and the Executive Committee and the Council of the Union met on September 13. The Inaugural Assembly was held on the morning of September 14. This first plenary session served two purposes: first, as a welcoming session, and second, to inform the Assembly of the activity of the previous three years.

The Assembly was addressed by Prof. Gino Cassinis on behalf of the Italian Organizing Committee, the Mayor of Rome, Prof. Gustavo Colonnetti on behalf of the National Research Council of Italy, and the Minister of Education. President Chapman of the International Union of Geodesy and Geophysics briefly outlined the history of the IUGG, mentioning that at the General Assembly in Rome in 1922, 105 were present but that at the time of the opening of this Assembly between 900 and 1000 had registered. He noted that only a very small number of the original 105 were participating in the current Assembly. He stressed that young scientists should be encouraged to attend these assemblies and that all nations should participate. General Secretary Laclavere outlined the activity of the preceding three years and the actions taken by the Executive Committee and the Council on the preceding day, noting that Bolivia, Brazil, Haiti, Hungary, Iran, and Sudan were elected to membership.

There were well over a thousand scientists and technologists present during the Assembly period. Many of these brought family members as guests. Forty-eight countries sent delegations as follows: Afghanistan, Argentina, Australia, Austria, Belgium, Bolivia, Canada, Chile, Czechoslovakia, Denmark, Ecuador, Egypt, Finland, France, West Germany, East Germany, Great Britain, Greece, Haiti, Hungary, India, Indonesia, Iran, Ireland, Israel, Italy, Japan, Luxemburg, Mexico, Morocco, The Netherlands, New Zealand, Nicaragua, Norway, Poland, Portugal, Saarland, Spain, Sweden, Switzerland, Syria, Tunisia, Turkey, Union of South Africa, U.S.S.R., United States, Vatican, and Yugoslavia.

All of the daytime meetings were held in the Palazzo dei Congressi, which served also as the headquarters for the General Assembly and provided an extensive area for the exhibit of geophysical instruments that was held concurrently. The opening session on September 14 was held in the Aula Magna of the Palazzo and for the first time introduced to the IUGG the multi-language facility, that is, as a speaker spoke, his address could be listened to over head phones in any one of five languages. On Tuesday afternoon, September 14, presidential addresses were given successively by President Coulomb of the Association of Terrestrial Magnetism and Electricity, President Gutenberg of the Association of Seismology and Physics of the Earth's Interior, and President Escher of the Association of Volcanology, and simultaneously by President Baeschlin of the Association of Geodesy. On Wednesday morning, September 15, President Ramanathan of the Association of Meteorology gave his presidential address, and in the afternoon the one in Oceanography was given by President Proudman. President Thijsse of the Association of Hydrology gave his presidential address on the morning of September 16.

Scientific sessions proceeded in the various Associations starting with the afternoon of September 14, and during the succeeding days all Associations had both morning and afternoon scientific sessions. In some instances, notably Geodesy, but also Seismology and the Physics of the Earth's Interior, Meteorology, Terrestrial Magnetism and Electricity, and Hydrology, two sessions were at times concurrently in progress. During the period of the Assembly, for example, the Association of Geodesy and its various sections had a total of 27 sessions. On the other hand, it was a proud boast of Oceanography that by carefully planning the schedule they had avoided concurrent sessions.



(1) K. R. Ramanathan (India), new President of IUGG; and J. T. Thijsse (The Netherlands), President, Assn. of Hydr. (2) G. Laclavere (France), General Secretary, IUGG, and daughter, Mlle. Jacqueline. (3) Informal reception following the audience with the Holy Father: front row, extreme right, retiring President Chapman and new President Ramanathan. (4) The Tison family of Belgium; L. J. Tison, Secretary, Assn. of Hydr.; Mlle. Marie-Chislaine, Mme. Tison, and Gerard. (5) Earl Droessler (U.S.A.); Sydney Chapman (Great Britain), James B. Macelwane, Chief Delegate from U.S.A.; and John N. Adkins (U.S.A.). (6) Foreground: K. R. Ramanathan (India), J. Tuzo Wilson (Canada), new Vice President, IUGG; and Lloyd V. Berkner (U.S.A.).

A number of joint programs were held, one, a Symposium on Storm Surges held by the Associations of Meteorology and Oceanography, extended over four sessions. Other included a Colloquium on the Problems of Atmospheric Electricity (Meteorology, and Terrestrial Magnetism and Electricity), Radioactivity (Seismology and the Physics of the Earth's Interior and Volcanology), Movements in the Earth's Core and Electrical Conductivity (Seismology and the Physics of the Earth's Interior, Terrestrial Magnetism and Electricity, and Volcanology), Colloquium on the Problems of the Mesosphere (Meteorology, and Terrestrial Magnetism and Electricity, two sessions), Geothermy (Seismology and the Physics of the Earth's Interior, and Volcanology), Actual Deformations and Isostasy (Geodesy, Seismology and the Physics of the Earth's Interior, and Volcanology), and Gravimetric and Seismic Interpretations of the Earth's Crust (Geodesy, Seismology and the Physics of the Earth's Interior, and Volcanology). Colloquia and symposia on various subjects were also presented in sessions of the individual Associations, such, for example, as the Colloquium on Radiation Balance in the Lower Stratosphere (below 50 km) and Substratosphere, in the Association of Meteorology.

The days were especially full not only with the many sessions of the various Associations but with other activities as well. There were various trips as, for example, to the National Institute of Geophysics in Rome to inspect facilities, in addition to the more extensive excursions planned for Sunday, September 19. There was an extensive program for family guests, who were given splendid opportunities to tour the various famous archeological and historical monuments and those of more recent development in Rome and its environs. Two evening sessions were held in the Planetarium near Piazza dell'Esedra in the area of the Baths of Diocletian, one of these being a series of films from the United States and the other relating to the French Emile Victor Expedition to Greenland.

On Sunday, September 19, the participants were offered the choice of four very interesting excursions. The first was to L'Aquila about two-thirds of the way over to the Adriatic, this being the provincial capital of Abruzzi, the second was in a northwesterly direction to the old towns of Cerveteri and Tarquinia, the third was to Ostia, old and new (the Port of Rome), and to Anzio, and the fourth was to the sulphur and borax hotsprings at Larderello and the steam power plants utilizing the heat of the Earth.

There was another excursion to the Alban Hills on Friday, September 24, on which occasion the audience with the Pope at his summer home at Castel Gandolfo was the high point. The Holy Father read a 20-minute message in French to the 900 persons present, citing the responsibility of scientists with the sociological implications of their work and the need to put these efforts to the good of mankind, and praised the plans for the International Geophysical Year for its prospects to these ends. Frascati and Rocca di Papa were also stops on this excursion which included an extensive trip through the Hills along Lake Albano and Lake Nemi, with return over the modern Appian Way. Other events included a symphony concert by the Symphony Orchestra of Radiotélévision Italienne in the Italian Forum. Although this was given on a very warm night, the concert was extremely well presented and well received. Another evening function was the reception of the City of Rome which was held in the roof garden of the Capitol in the neighborhood of the Victor Emmanuel Monument near Piazza Venezia.

One hundred and sixty-four delegates, participants, and guests were in attendance from the United States as follows: Leason H. Adams and daughter, Mrs. Madeline Adams Jones; Carl I. Aslakson and Mrs. Aslakson; John N. Adkins; Wallace W. Atwood, Jr., and mother, Mrs. W. W. Atwood, Sr.; James R. Balsley; Roland F. Beers and Mrs. Beers; K. Hilding Beij; Hugo Benioff and Mrs. Benioff; Lloyd V. Berkner, Mrs. Berkner, and daughter, Miss Phyllis Berkner; Francis Birch and Mrs. Birch; J. A. B. Bjerknes, Mrs. Bjerknes, and daughter, Miss Kirsten Bjerknes; Harry F. Blaney and Mrs. Blaney; N. T. Bobrovnikoff; Carl B. Brown; Harrison S. Brown and Mrs. Brown; Walter H. Bucher; Horace R. Byers and Mrs. Byers; D. S. Carder; Phil E. Church; Harry L. Coggins; John A. De Pue and Mrs. De Pue; Robert S. Dietz; L. P. Disney, Mrs. Disney, Mrs Frances De Long, and Mrs. Catherine M. Viehmann; Robert F. Dressler; Earl G. Droessler; C. T. Elvey; K. O. Emery; Maurice Ewing; Henry Faul and Mrs. Faul; Richard H. Fleming; Willis B. Foster; John C. Freeman, Jr.; François N. Frenkiel; Herbert Friedmann and Mrs. Friedmann; N. C. Gerson and Mrs. Gerson; Beno Gutenberg and Mrs. Gutenberg; Ross R. Heinrich; Albert J Hoskinson and Mrs. Hoskinson; Floyd W. Hough and Mrs. Hough; Edward O. Hulburt and Mrs. Hulburt; Ira A. Hunt; C. E. Jacob; Woodrow C. Jacobs; Authur W. Johnson and Mrs. Johnson; Walter P. Johnson, III; Joseph Kaplan; Lewis D. Kaplan; Jean I. F. King; S. A. Korff; Walter D. Lambert; Walter B. Langbein; Linnea G. Lauré and sister, Miss Esther L. Lauré; Gunnar Leifson; Anthony M. Lunetta and Mrs. Lunetta; John Lyman; Joseph Lynch; James B. Macelwane (Chief Delegate); P. W. Mange; John Putnam Marble and Mrs. Marble; William Markowitz; Brian H. Mason and

Mrs. Mason; N. A. Matson; Arthur E. Maxwell; Henry A. Miley; Maynard M. Miller; Walter H. Munk; J. H. Nelson; Homer E. Newell, Jr.; Hugh Odishaw; C. L. Pekeris and Mrs. Pekeris; James A. Peoples, Jr.; Paul M. Pepper; Helen B. Pettit; Richard W. Philbrick; Frank Press; Victor H. Regener; F. W. Reichelderfer and Mrs. Reichelderfer; Roger R. Revelle, Mrs. Revelle, and two daughters, Miss Mary Ellen Revelle and Miss Carolyn Revelle, and son, William Roger; Donald A. Rice; Malcolm Rigby; George P. Rigsby; Franklin E. Roach; Elliott B. Roberts and Mrs. Roberts; C. G. Rossby; Walter E. A. Ruska; Pierre St. Amand; A. Nelson Sayre, Mrs. Sayre, and daughter, Miss Elizabeth Sayre; Milton O. Schmidt; Harold A. Sears and Mrs. Sears; Mary Sears; A. H. Shapley; E. H. Sheridan; André C. Simonpietri and Mrs. Simonpietri; S. F. Singer; L. B. Slichter and Mrs. Slichter; Waldo E. Smith; Athelstan F. Spilhaus; John Strong; R. F. A. Studds and Mrs. Studds; Max Suter and Mrs. Suter; Harold C. Urey; Victor Vacquier and mother, Mrs. Tatiana I. Vacquier; John Verhoogen; William A. von Arx; Harry W. Wells and Mrs. Wells; Harry Wexler; C. A. Whitten and Mrs. Whitten; Robert L. Wiegel and Mrs. Wiegel; Harold G. Wilm; James T. Wilson, Mrs. Wilson, and daughter, Miss Deborah Wilson; J. A. Woida; John Wolbach; S. P. Worden; J. L. Worzel; and Marshall S. Wright, Sr.

The final plenary session was held on Saturday morning, September 25, in the Aula Magna of the Palazzo dei Congressi, and at this meeting it was announced that the Council had approved holding the Eleventh General Assembly in 1957 in Buenos Aires, Argentina. The officers of the Union elected were as follows: President, K. R. Romanathan of India; Vice Presidents, J. Tuzo Wilson of Canada and C. A. Levene of Argentina. (General Secretary Laclavère was elected in Brussels for a six-year term.) To succeed J. Tuzo Wilson on the Finance Commission, Fritz Gassmann of Switzerland was appointed. Continuing members on the Finance Commission are K. Hilding Beij of the United States, A. F. Doodson of Great Britain, M. Goldschmidt of Israel, and J. Vignal of France.

The results of the Association elections and Committee designations were as follows:

Geodesy--President, J. de Graaff-Hunter (Great Britain); Vice Presidents, Gino Cassinis (Italy) and Riggi O'Dwyer (Argentina); Secretary, P. Tardi (France); Deputy Secretary, J.-J. Levallois (France); Honorary President (member of Executive Committee), C. F. Baeschlin (Switzerland) (with F. A. Vening Meinesz and W. D. Lambert continuing; also N. E. Nörland continuing as a member of the Executive Committee). Section of Triangulation--President, C. A. Whitten (U. S. A.); Secretary, Antonio Marussi (Italy). Section of Leveling--President, Paolo Dore (Italy); Secretary, O. Simonsen (Denmark). Section of Geodetic Astronomy--President, J. F. Cox (Belgium); Secretary, H. S. Jelstrup (Norway). Section of Gravity--President, B. C. Browne (Great Britain); Secretary, Donald A. Rice (U. S. A.); Assistant Secretary, Suzanne Coron (France). Section of Geoid--President, Guy Bomford (Great Britain); Secretary, E. H. Thompson (Great Britain).

Seismology and Physics of the Earth's Interior--President, K. E. Bullen (Australia); Vice Presidents, Kiyoo Wadati (Japan) and Ernst Wanner (Switzerland); Secretary, Jean-Pierre Rothé (France); Executive Committee: B. Gutenberg (U. S. A.), Marcus Båth (Sweden), Simon Gershanik (Argentina), J. H. Hodgson (Canada), and R. Ingram (Ireland). Committee for the International Seismological Summary--Chairman, Harold Jeffreys (Great Britain); members, I. Lehmann (Denmark), B. Gutenberg (U. S. A.), J. H. Hodgson (Canada), J. B. Macelwane (U. S. A.), R. Stoneley (Great Britain), and E. Vesanen (Finland). Commission on the Physics of the Earth's Interior--Tectonophysics, F. A. Vening Meinesz (The Netherlands); Gravimetric Interpretation, J. Goguel (France); Radioactivity and Geothermy, Edward Bullard (Great Britain) and J. Tuzo Wilson (Canada); Elasticity and Plasticity, Harold Jeffreys (Great Britain) and R. Stoneley (Great Britain). Commission for the Study of European Seismological Problems--President, W. Hiller (Germany); Secretary, P. Caloi (Italy); members, M. Båth (Sweden), J. Bonelli Rubio (Spain), M. J. Debrach (Morocco), H. A. Ferreira (Portugal), A. Galanopoulos (Greece), G. Grenet (Algeria), R. Ingram (Ireland), A. Kvale (Norway), I. Lehmann (Denmark), J. Mihailovic (Yugoslavia), E. Peterschmitt (France), Nuriye Pinar (Turkey), J. C. Scholte (The Netherlands), E. Tillotson (Great Britain), M. Toperczer (Austria), E. Tryggvason (Iceland), J. M. Van Gils (Belgium), E. Vesanen (Finland), and E. Wanner (Switzerland).

Meteorology--President, C.-G. Rossby (U. S. A.); Vice Presidents, Jacques Van Mieghem (Belgium) and Horace R. Byers (U. S. A.); Secretary, Reginald C. Sutcliffe (Great Britain); Executive Committee, Arlette Vassy (France), C. H. B. Priestley (Australia), and Fritz Möller (Germany). Ozone Commission--President, G. M. B. Dobson (Great Britain); Secretary, Charles Normand (Great Britain). Radiation Commission--President, W. Mörikofer (Switzerland); Secretary, F. Möller (Germany).

Geomagnetism and Aeronomy (formerly Terrestrial Magnetism and Electricity)--President, Julius Bartels (Germany); Vice Presidents, Joseph Kaplan (U.S.A.) and J. M. Rayner (Australia); Secretary, V. Laursen (Denmark); Executive Committee, Sydney Chapman (Great Britain), Elliott B. Roberts (U.S.A.), M. Nicolet (Belgium), M. Hasegawa (Japan), Leonidas Slaucitajs (Argentina), and Jean Coulomb (France, retiring Association President).

Oceanography--President, H. Mosby (Norway); Vice Presidents, J. N. Carruthers (Great Britain) and J. Rouch (France); Secretary, R. H. Fleming (U.S.A.); Deputy Secretary, B. Kullenberg (Sweden); Executive Committee, Günther Böhnecke (Germany) and J. Proudman (Great Britain), with P. Groen (The Netherlands) and H. U. Sverdrup (Norway) continuing. Committee on Tides--Chairman, J. Proudman (Great Britain); Secretary, J. B. Schijf (The Netherlands); members, L. P. Disney (U.S.A.), J. E. Fjeldstad (Norway), A. Gougenheim (France), W. Horn (Germany), N. Menendez (Spain), M. Tenani (Italy), and K. Terada (Japan). Committee on Mean Sea Level and its Variations--Chairman, J. D. Nares (Monaco); Secretary, A. T. Doodson (Great Britain); member, L. P. Disney (U.S.A.). Committee on Nomenclature of Ocean Bottom Features--Chairman, J. D. H. Wiseman (Great Britain); Secretary, J. D. Nares (Monaco); members, A. F. Bruun (Denmark), K. O. Emery (U.S.A.), H. H. Hess (U.S.A.), F. Koczy (Sweden), Ph. H. Kuenen (The Netherlands), and T. Stochs (Germany). Committee on Oceanographical Observations from Atlantic Weather Ships--Chairman, J. R. Lumby (Great Britain); Secretary, O. H. Saelen (Norway); members, A. Gougenheim (France), J. Lyman (U.S.A.), K. M. Rae (Great Britain), J. W. Termijtelen (The Netherlands), and H. Thomsen (Denmark). Committee on Preparation of Technical Handbook on Physical Oceanography--Chairman, H. U. Sverdrup (Norway); members, G. Böhnecke (Germany), J. N. Carruthers (Great Britain), G. E. R. Deacon (Great Britain), A. Gougenheim (France), E. C. LaFond (U.S.A.), H. Mosby (Norway), and N. W. Rakestraw (U.S.A.). Committee on Questions Concerning Preparation of a Bibliography--Chairman, H. U. Sverdrup (Norway); Secretary, P. Groen (The Netherlands); members, H. L. G. Bencker (Monaco), J. N. Carruthers (Great Britain), L. Fage (France), J. R. Lumby (Great Britain), R. B. Montgomery (U.S.A.), R. Revelle (U.S.A.), and J. T. Rund (Norway). Committee on the Geophysical Year 1957-1958--Chairman, R. H. Fleming (U.S.A.); Secretary, G. E. R. Deacon (Great Britain); members, G. Böhnecke (Germany), A. Defant (Austria), A. Gougenheim (France), M. S. Longuet-Higgins (Great Britain), H. Mosby (Norway), and W. Munk (U.S.A.). Committee on Storm Surges--Chairman, A. T. Doodson (Great Britain); Secretary, J. B. Schijf (The Netherlands); members, L. P. Disney (U.S.A.) and W. Horn (Germany). Committee on Current Measurements--Chairman, G. Böhnecke (Germany); Secretary, W. S. von Arx (U.S.A.); members, J. N. Carruthers (Great Britain), J. E. Fjeldstad (Norway), H. Mosby (Norway), and V. Romanovsky (France). Joint Commission on Oceanography--Appointed by the IUGG (IAPO): President, J. D. H. Wiseman (Great Britain); Secretary, C. D . Ovey (Great Britain); members, C. W. Correns (Germany), M. Ewing (U.S.A.), R. H. Fleming (U.S.A.), Ph. H. Kuenen (The Netherlands), H. Pettersson (Sweden). Appointed by IUBS: Members, A. F. Bruun (Denmark), L. Fage (France), R. Revelle (U.S.A.), Mary Sears (U.S.A.). Advisory Councillors: F. Bernard (France), Edward Bullard (Great Britain), L. H. N. Cooper (Great Britain), G. E. R. Deacon (Great Britain), A. Defant (Austria), C. Fleming (New Zealand), M. H. Hill (Great Britain), F. Koczy (Sweden), Th. Monod (France), J. D. Nares (Monaco), J. Rouch (France), H. U. Sverdrup (Norway), H. C. Urey (U.S.A.), and C. E. ZoBell (U.S.A.).

Volcanology--President, Alfredo Rittmann (Switzerland); Vice Presidents, G. C. Goergalas (Greece) and Louis Glangeaud (for Paleovolcanology) (France); Secretary, Francesco Signore (Italy); Editor of Catalogue of Volcanoes, M. Neumann van Padang (The Netherlands). Other members of the Executive Committee will be chosen by the new officers.

Hydrology--President, J. T. Thijsse (The Netherlands); Vice Presidents, G. de Marchi (Italy) and H. G. Wilm (U.S.A.); Secretary, L. J. Tison (Belgium). Commission on Subterranean Waters--President, A. Nelson Sayre (U.S.A.); Vice President, Wilhelmus Krul (The Netherlands); Secretary, Stevenson Buchan (Great Britain). Commission on Surface Waters--President, Dino Tonini (Italy); Vice Presidents, Howard L. Penman (Great Britain) and Vujica Yevdjevic (Yugoslavia); Secretary, Louis Serra (France). Commission on Snow and Ice--President, Robert Haefeli (Switzerland); Vice Presidents, Richard Finsterwalder (Germany) and Albert Bauer (France); Secretary, Patrick D. Baird (Great Britain). Commission on Land Erosion--President, J. Tixeront (Tunisia); Vice Presidents, Yousef M. Semeika (Egypt) and Pietro Frosini (Italy); Secretary, Louis Gottschalk (U.S.A.). Committee on Hydrologic Instruments--Chairman, J. B. Schijf (The Netherlands), W. B. Langbein (U.S.A.), another appointment pending. Committee on Precipitation Measurements (jointly with the Association of Meteorology)--Chairmen, L. Serra (France, Hydrology) and L. Poncelet (Belgium, Meteorology); E. L. Hamilton (U.S.A.), and Max Kohler (U.S.A.), other appointments pending. Committee on Characteristics of Rivers--Chairman, Wilhelm Friedrich (Germany); other appointments pending.

In the final plenary session the following matters were noted and actions of the Council were approved. Word had come from the U.S.S.R. that an application would be forthcoming soon from that country. The General Secretary noted that all dues were paid up to date, that UNESCO subventions for publications, permanent services, and symposia had increased somewhat during the last three years, and that steps are being taken to arrange for the more firm financing of the permanent services of the Union which are to be specifically defined in the By-Laws. He noted that the tasks of the office of the Union were getting heavier, particularly because of the fact that the number of adhering countries is increasing. This raises certain problems that will need to be faced in the future. He noted that the publication of the Newsletter is now firmly established, that its financing is good, being supported through advertising, grants, and subscriptions, and that 2300 copies are currently being printed. The General Secretary stated that messages had been received from various countries and that the Philippine Government had expressly sent regrets that it was unable to send a delegate to the Assembly. He remarked that a message had been sent, following the first plenary session, to John A. Fleming, Honorary President of the AGU, formerly very active in his promotion of the IUGG and ICSU.

At the final plenary session each Association President was called upon to give a brief report, and in connection with these the resolutions of the various Associations were approved for transmission by the IUGG. At this meeting retiring President Coulomb of the Association of Terrestrial Magnetism and Electricity announced that the Association had elected to be called henceforth the Association of Geomagnetism and Aeronomy.

The General Secretary noted that heavy expenses are incurred by the Union and its Association for publication, that they have sought out ways and means of meeting this burden more satisfactorily, and that arrangements are being entered into with the Butterworth's Publications, Ltd., of England to undertake the handling of the publications on a commercial basis.

It was noted that a working arrangement had been developed with respect to the World Meteorological Organization, the text of which in due course will be published in the Newsletter of IUGG. Also noted were plans for an arrangement with the Pan American Institute of Geography and History relative to cooperation between the two organizations.

A resolution relative to scientific research work on the Continental Shelf with respect to open publication had been endorsed for forwarding through appropriate channels to the United Nations.

It was agreed likewise to remove from the Statutes the provisions regarding delegates and place them in the By-Laws, with modification defining them more definitely in relation to voting power in the Union and its Associations and Commissions. Other scientists and technologists should be called participants rather than guests.

The Finance Committee noted that the finances of the Union and of its Associations are in good order and that the firm income of the Union is now about £12,000 per year. It was also approved that the number of categories available for membership be increased from eight to 15 but that the present rate of £100 per category should be retained and that the provisions for voting in the Statutes should remain as at present. The items involving changes in the Statutes and By-Laws cannot be effective until final action is taken at the next General Assembly.

Thanks were voted General Secretary Laclavère and Mme. and Mlle. Laclavère for the important and effective work that they have carried on during these last three years. Thanks were also extended to the President of Italy for his formal message of welcome, to the Holy Father for his reception and address, to the Government of Italy for its support of and hospitality to the General Assembly, to the City of Rome for its reception, to the National Research Council of Italy for its work in connection with the Assembly, and to the Italian National Committee and the Italian Organizing Committee and their ladies for their great work. Thanks were also extended to retiring President Chapman, and to Mrs. Chapman for her important support of President Chapman's work.

The Assembly adjourned at noon on September 26, 1954.

Following the General Assembly, a number of the participants joined one of the four excursions arranged: (1) to Naples, Capri, Sorrento, and Pompeii; (2) to Naples, Vesuvius, Sorrento, and Capri; (3) to Naples, Palermo, Messina, Taormina, and Etna; and (4) to Naples, Aeolian Islands (Stromboli), Messina, Taormina, and Etna.

From September 27-30, the Committee on the International Geophysical Year (CSAGI) and its various working groups met in connection with plans for the Geophysical Year, 1957-1958.

Waldo E. Smith

REPORT OF THE SPECIAL COMMITTEE ON THE ROLE OF THE METEOROLOGY SECTION OF THE AMERICAN GEOPHYSICAL UNION AND THE AMERICAN METEOROLOGICAL SOCIETY

Michael Ference, Jr., Chairman

Bernard Haurwitz Vincent J. Schaefer

There is unanimity of agreement that there exists no basic conflict of interests between the activities of the AMS and those of the Section on Meteorology of the AGU. It is natural and proper that meteorology should constitute an important scientific section of the AGU, for it is one of the principal geophysical sciences. Therefore, it is to the best professional interests of meteorologists that this activity of the AGU be vigorously supported.

It is also our strong conviction that it is advantageous to meteorologists to have two outlets for publications of scientific papers. The Transactions provide a medium for the publication of scholarly papers, particularly those of rather wide geophysical significance, and authors of such papers should be encouraged to use the Transactions. There are many professional meteorologists who are interested in and receive stimulation from the broad implications of the geophysical sciences. The AGU and its activities provide the basis for participation in such allied fields as oceanography, geomagnetism, etc. This type of cooperative exchange of common interest knowledge should be strengthened not weakened.

The Committee is of the opinion that a concerted effort should be made to exploit this unique position that the Section of Meteorology of the AGU enjoys by continuing to bring geophysical scientists together at technical meetings and colloquia and by providing them a suitable medium for publication. As a practical suggestion, the Program Chairman of the Section on Meteorology might arrange to include selected contributions from other Sections of the AGU as was so successfully done with Hydrology, with Geomagnetism (upper atmosphere), and with Oceanography.

Regional Meeting in Portland, Oregon--An organizational and technological meeting was held in the Pacific Northwest Region at Portland, Oregon, November 5, 1954, with about 100 in attendance. The meeting was arranged by an ad hoc committee consisting of C. C. McDonald, Chairman, T. H. Campbell, Frank Neumann, and M. S. Sachs, appointed at the request of members in the Region, with program arrangements in charge of M. S. Sachs and local arrangements in charge of Norbert H. Leupold. A Committee on Statutes and By-Laws, under the chairmanship of T. H. Campbell, presented a report covering Statutes and By-Laws for the projected Region. These were adopted with minor changes, and the Regional Committee was elected as follows: Representing Hydrology, T. H. Campbell, C. C. McDonald, and M. S. Sachs; representing Meteorology, Peter B. Boyer and V. P. Schermerhorn; representing Oceanography, C. A. Barnes; representing Geodesy, Fred Natella; and representing Seismology, Frank Neumann. C. C. McDonald was designated as the Chairman and V. P. Schermerhorn as the Secretary-Treasurer. An excellent program was presented consisting of 12 papers, including a Symposium on Applied Hydrology.

SPECIAL ANNOUNCEMENTS

Student subscription rates--A subscription rate of $4.00 per calendar year has been set for bona fide full-time graduate and undergraduate students upon certification to that effect by the Head of the Department in which the student is majoring. This rate is not available to instructors or others who are essentially half- to full-time workers. The payment of $4.00 must accompany the certificate and order to eliminate the expense of correspondence and billing. The rate is offered strictly as a service to education, and to keep the cost of handling to a minimum, all such subscriptions are entered only on the calendar-year basis. They are renewable only with a new certificate and may continue for a maximum of five years. A certificate form will be supplied upon request.

Pacific Southwest Regional Meeting, University of California at Berkeley, February 4-5, 1955--Plans are progressing well for this Thirty-Fourth Regional Meeting which will be held on the campus of the University of California at Berkeley, February 4-5, 1955. J. W. Johnson, Professor of Engineering at Berkeley, is General Chairman of the meeting; and David K. Todd, Professor of the Division of Civil Engineering and Irrigation at Berkeley, is Chairman of the Program Committee. Martin R. Huberty, Professor of Irrigation of the University of California at Los Angeles, is the Chairman of the Regional Committee; and R. Corday Counts, Jr., of the U. S. Weather Bureau at Burlingame, California, is the Regional Secretary. Interested persons should get in touch with one of these.

Thirty-Sixth Annual Meeting, Washington, D. C., May 2-4, 1955--Your attention is called to the extended notice concerning this meeting on page 865 of the October issue of the Transactions. Note that titles and abstracts of papers for the program should be sent in as soon as possible, not later than March 10, 1955. Abstracts must be informative, concise, and not more than 150 words. Remember that Sections may close programs prior to March 10, so send information in early. Complete manuscripts should be in the AGU office by April 15, with advice as to whether the paper is being submitted for the Transactions or only for information. In the former case, three complete copies should be sent, double spaced, and in general accord with AGU's "Suggestions to Authors." Also, send word concerning projection equipment required. A standard sized (3 1/4 × 4 inches) slide projector will normally be available, but other facilities will be provided only upon word of requirements. Communications should be sent to the appropriate Section Secretary or Program Chairman [see October issue, page 865] or to the AGU office. If you do not have experience in proper preparation of figures and tables for the making of slides, write to the AGU office requesting information on this.

In preparing a paper for presentation, keep in mind that the requirements are quite different from those for publication. A paper for presentation might be compared to a thread or chain, while a published paper is more on the order of a fabric. And, in presentation, keep in mind that you should face the audience and speak slowly, distinctly, and briefly, and avoid complicated mathematics. The mathematical presentation should appear in the published paper.

Block bookings have been made at three hotels as follows:

Roger Smith Hotel, Pennsylvania Avenue at 18th Street, N.W.

Willard Hotel, Pennsylvania Avenue at 14th Street, N.W.

Raleigh Hotel, Pennsylvania Avenue at 12th Street, N.W.

Most of the block-booked rooms are in the Roger Smith Hotel (the one nearest the National Academy of Sciences where most of the sessions will be held), and the Willard Hotel. Make your room reservation early directly with the hotel of your choice, citing the AGU block booking if you write to one of the three hotels noted.

Eleventh General Assembly, International Union of Geodesy and Geophysics--The Eleventh General Assembly of IUGG will be held in Buenos Aires, Argentina, in 1957. The dates are not yet fixed. Watch Special Announcements for further details.

The "every-member-get-a-member" effort--On the front flyleaf of the August issue of the Transactions was a letter to the membership from President Macelwane pointing out some of the objectives of AGU, and urging members to bring qualified non-members of which there are many into the membership in order that we might attain these ends without an increase in dues. The objectives cited included the plan to reduce our backlog of papers so that the average interval from receipt of paper to publication is reduced to six months, and to improve the format by justification of the right-hand margin and otherwise.

This letter was followed by a letter by direct mail from Membership Chairman Hiatt which enclosed a membership application form and other material. There has been some response to these letters, but the hoped-for response has not been realized. This issue of the Transactions is in two parts, the second part is a Membership Directory which should be of aid in telling who of your colleagues is not now a member. In the back of directory is another application form.

Have you done what you can to aid in this matter?

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